NASA-CR-195505

NASW-4435

IN-20-CR

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Embodiment Design for a Multipropellant Resistojet

(NASA-CR-195505) EMBODIMENT DESIGN FOR A MULTIPROPELLANT RESISTOJET (Texas Univ.) 59 p

N94-24834

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G3/20 0204249

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May 3, 1993

This document presents the embodiment design of a multipropellant resistojet to use as an auxilliary propulsion system on the Space Station. Such a system is necessary to counteract atmospheric drag effects encountered by the Station in its orbit. NASA specifications are strictly followed with emphasis on reliability, operating life, multipropellant capability, and exhaust emission control. Several design variants are considered, and the final solution is a resistojet with an electronic pressure regulator, variable control, an internal flow heater, and a conical nozzle. To construct the resistojet, the important components are resolved independently, and then integrated with secondary units. The document also includes engineering drawings of the final design with assembly instructions. Before final utilization, a prototype testing is recommended to uncover possible problems.

Contents

Nomenclature

English Variables	
A	area
A_{to}	outer surface area of the heater tube
C	speed of sound
D_{ti}	inside diameter of tube
D_{to}	outside diameter of tube
D_w	diameter of resistor wire
E	Young's modulus
F_{i-j}	view factor of surface i seen from surface j
g_c	gravity proportional constant
H	enthalpy
h	heat transfer coefficient
I	current
k	thermal conductivity
L_w	length of resistor wire
L_t	length of the heater tube
M	Mach number
m	mass flow rate
n	number of radiation shields
P_{in}	electrical power into the resistor
P	pressure
P_o	stagnation pressure
q	heat flux
Q_n	heat transfer between radiation shields
R	electrical resistance of heater
T	thrust
T_m	melting temperature
T_i	temperature at i
V	velocity

Greek Variables	
ΔT_{LM}	logarithmic mean temperature difference
ε	emissivity
η	overall efficiency of the heater
ρ	electrical resistivity
σ_{mr}	modulus of rupture
%T	percentage of ideal thrust
θ	nozzle half-angle
γ	ratio of specific heat
$\hat{\partial}$	density

Problem Clarification

To counter the effects of drag on an object orbiting in the upper atmosphere of the Earth, some method of propulsion is required. Otherwise, the orbit decays. For extended use with the Space Station, such a propulsion system should minimize propellant payload requirements, be reliable, have an extended operating life, and control exhaust emissions that could disturb station operations [Larson, 1987].

Resistojets are ideally suited for the needs of the station since waste gases produced on the station are used as the propellant, and no combustible or massive propellant must be shuttled to the station as payload [Larson, 1987]. In one mode of operation, the high temperature mode, the waste gases are heated by an electrical resistance heater and then expanded through a nozzle to provide thrust to counter the effect of drag. If waste gases must be expelled, yet no thrust is required, a warm mode of operation is used. A power and flow control system, integrated into the station control system, can be installed to make the system self-sufficient and efficient. Also, a plume shield can be installed to control emissions for environmental safety. Therefore, the resistojets can be designed for reliable operation over their operating life, minimal cost, and for compliance with National Aeronautics and Space Administration (NASA) specifications.

This paper presents the detailed embodiment design of a resistojet for Space Station integration. The methodology followed in the conceptual design is presented, and the final solution is justified. Then, key issues are individually identified and resolved. Having constructed the components of the resistojet, the components are integrated into a final assembly. Finally, the resistojet is evaluated and procedures are suggested for prototype testing.

Conceptual Design

The key specifications defining the functional requirements and constraints for the resistojet system were supplied by NASA. For brevity, only these key specifications are included in the report (see Table 1). A complete specification list is included in Appendix A.

The critical specifications not defined by NASA include the seal and material constraints. Seals are necessary to make the resistojet system a closed loop system in the interest of environmental safety. Safety factors have been included in the specification to insure these seals will not rupture due to high pressure, or melt due to high temperatures. Also, material constraints are the limiting factors of the resistojet design. Materials appropriate for the entire range of operation are important. Hence, a safety factor for all materials is also included as part of the design.

Based on these key specifications, a complete functional analysis and justification was constructed (see Appendix B). The function structure, shown in Figure 1, is included to show the flow of material, energy, and information through the system.

Table 1. Critical Specifications

F/C	D/W	
F	D	Operational lifetime of 10,000 hours (10,000 cycles over 18 years)
F	D	Generate 50-350 millipounds of instantaneous thrust
C	D	Materials must withstand temperature and pressure ranges of operation
F	D	Operate with an average power < 125 W, with a peak power of 500 W
F	D	Heat waste gases from 0 - 1400 °C
F	D	Withstand an input gas pressure of 80-1000 psia from the storage tank
F	D	Accommodate multipropellant mixtures, primary gases: (H_2O, N_2, Air, Ar, CO_2)
F	D	Impulse over life of operation ~ $2x10^6$ lbf/s
C	D	Control waste gas exhaust plume so as not to contact the station
C	D	Points of attachment of the heater must be < 300 °C
C	D	Sealants must withstand temperatures and pressures ranges (safety factor of 1.5)

From the functional analysis, the primary functions essential to the operation of the resistojet were chosen. They include the heater, the nozzle, and the flow and power controllers, where the problem of plume control is considered a nozzle function. With each of these essential functions, brainstorming was implemented to introduce possible design variants. The resulting list of designs for the resistojet system is shown in Table 2.

Before constructing a decision matrix to choose the final design, the inferior designs were eliminated due to the large number of possible combinations (160). First, the fixed valve and simple orifice flow control variants are combined into a single variant, because both perform the same function of setting a pressure drop dependent on the upstream pressure. Also, the variable valve and the mechanical pressure regulator have been combined into one concept that gives a constant downstream pressure.

In considering the power control variants, since resistojet operation is not continuous, constant heating was eliminated because of its low efficiency. Also, various power control options were eliminated because of their incompatibility with the flow control options. For use with the simple orifice, both two setting and on/off control were eliminated based on the fact that fine power control is needed if the pressure is allowed to change with time without "intelligent" control. Similarly, on/off power control with a mechanical pressure regulator provides neither a variable flow nor a variable input power, and can be eliminated.

In considering the nozzle, the function was defined as the means to expand the heated

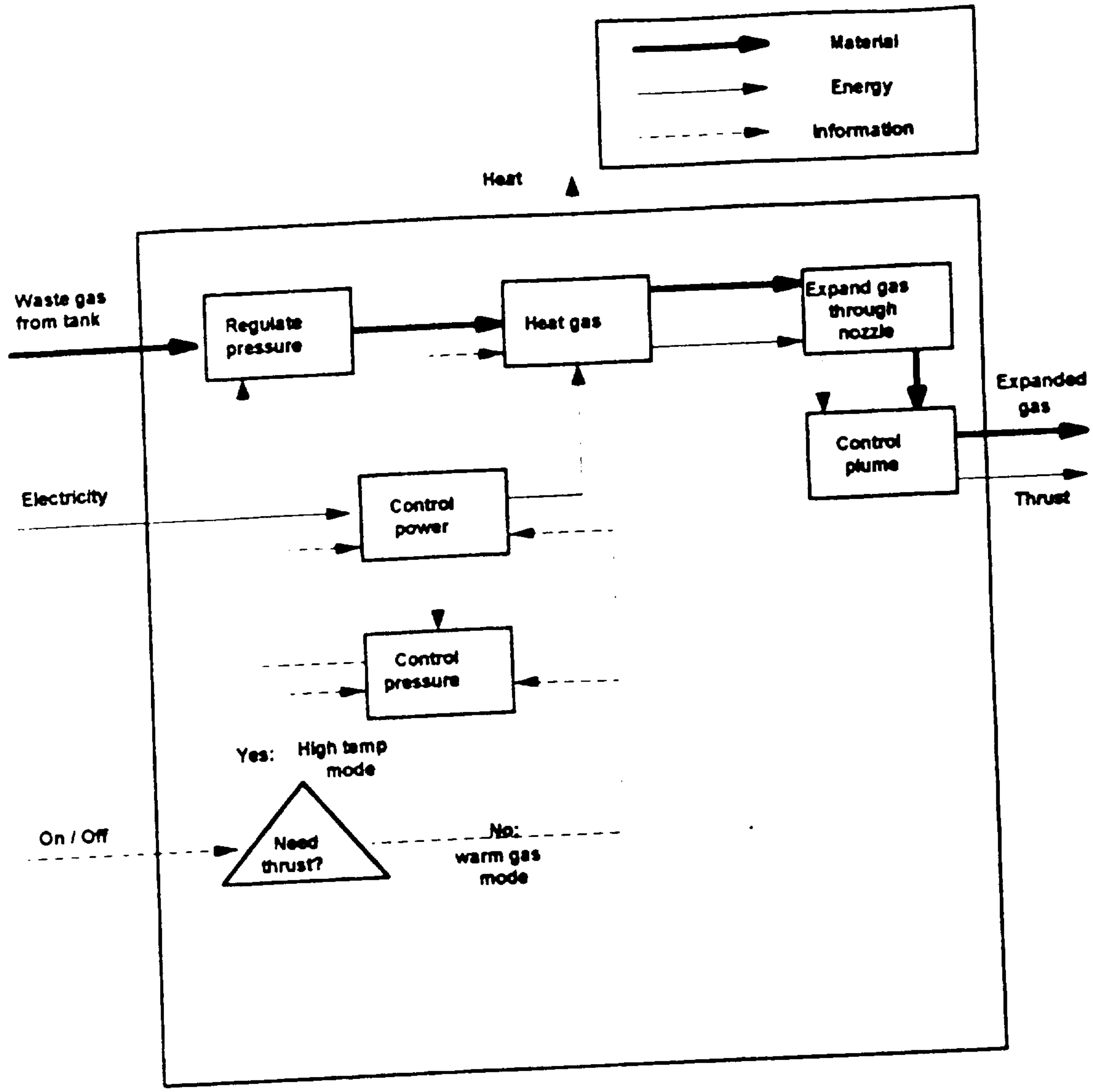


Figure 1. Function Structure

Table 2. Design Variants

Flow control	Power Control	Heater	Nozzle
Electrical Pressure Regulator	constant	external flow/internal heater	contoured or bell-shaped
Mechanical Pressure Regulator	on/off	internal flow/external heater	Expansion/ Deflection
			Plugged
Simple Orifice	variable		Conical
Fixed Valve	two-setting		
Variable Valve			

gases exiting the heater to provide thrust, and to exhaust the cooled gas away from the Space Station. It should be noted that each of the nozzle geometries considered make up the diffuser section of a converging-diverging nozzle. The converging-diverging geometry is the only feasible nozzle design, since the waste gases exiting from the heater at a subsonic velocity must be accelerated to supersonic speeds.

The most efficient nozzle geometry in gas expansion is contoured, or bell-shaped. However, this geometry does not yield effective control of the exhaust plume. Without exhaust plume control, waste gas contact with the station, environmental contamination, or the deposition of precipitates on sensitive surfaces (i.e. the solar panels) could occur. Through extensive research, Sutton found that the conical nozzle geometry, with a plume shield, offers optimum plume control [1975]. Since this conical geometry lacks only a few percent in efficiency compared to the contoured nozzle, it was selected as the design to pursue.

For the heater, advantages and disadvantages were listed for each variant. With the external flow/internal heater, intricate parts requiring complex manufacturing are necessary [Pugmire, et al., 1986]. These parts include a thin, tightly wound resistor coil, which must fit inside the 5-10 mm diameter gas pipe, a suspended inner core directly in the path of the high temperature and high speed gas flow, and an internal resistor. With these components, the heater will have a short life expectancy, in that the thin coil introduces a weak surface directly into the high speed flow of the hot gas. Also, high temperatures inside the inner core, and a poor force distribution on the core, which could result in creep under high temperatures, limit the heater life. On the other hand, efficiency with internal heating is an advantage. The fact that the flow is external, indicates that heat leaving the core must flow through the propellant. Therefore, minimal insulation is required.

In the case of the external heater, the efficiency is lower due to the radiation of heat to space. Thus, good insulation is necessary. However, compared to the internal heater, this design is simpler to manufacture, consisting of fewer parts and an external resistor which does not require such a small coil diameter. Also, this heater has a longer life expectancy, since areas in contact with the hot gases are smooth surfaces. That is, the resistor coil can be placed on the exterior of the gas pipe, rather than directly in the flow. Also, since the outer shell is easy to mount with a good force distribution, greater reliability is expected.

The only major disadvantage for the external heater is efficiency, which can be corrected with good insulation. However, the disadvantages associated with using the internal heater are defined by the resistojet specifications. Thus, external heating is selected as the design to pursue.

Four concept rating factors were chosen from the key specifications with which to compare the remaining designs in the decision matrix: thrust control, efficiency, reliability, and cost. Thrust control was based on how fine the thrust could be controlled with the power and flow control system, while efficiency was based on maximizing the power output to input ratio. Reliability was based on the resistojet's ability to operate within specifications in every foreseeable case, and cost was based on weight (i.e. as shuttle payload), manufacturing, and operating costs. Selection of rating factor weights, and the design variant weights, is included in Appendix C. The resulting decision matrix is shown in Table 3.

Table 3 Conceptual Decision Matrix

Design Variants	Thrust Control	Efficiency	Reliability	Cost	Total
Flow/Power control	35 %	27 %	27%	11%	100 %
Orifice/Variable	1.75 / 5	1.35 / 5	2.43 / 9	0.99 / 9	6.52
Mech./2 setting	1.75 / 5	1.89 / 7	1.89 / 7	1.1 / 10	6.63
Mech./Variable	3.15 / 9	1.89 / 7	1.89 / 7	0.99 / 9	**7.92**
Elec./2 setting	2.45 / 7	2.43 / 9	1.35 / 5	0.77 / 7	7.00
Elec./On-Off	2.45 / 7	2.43 / 9	1.35 / 5	0.77 / 7	7.00
Elec./Variable	3.5 / 10	2.7 / 10	1.35 / 5	0.55 / 5	**8.10**

Note: Each design variant includes the external heater/internal flow and the conical nozzle.

In deciding which of the two final design variants to pursue with the embodiment design phase, the final decision was based on a more in depth look at the concept rating factors used in the decision matrix. This more in depth study focused on the major differences between the two variants: how fine of control is attainable, and how efficient the system operates. Costs between the two varied widely; however, no maximum cost was specified by NASA. Thus, it was not considered. Similarly, reliability variations were not considered because with both designs, the extended life specification is met.

Both devices have fine thrust control, since the heater input power can be varied to be any value between 0 and 500 W. Yet, the electronic pressure regulator is slightly better in that its flow control can also be varied without physical intervention. Furthermore, the fact that the flow control can be varied gives the electronic pressure regulator better efficiency. That is, a system which has fine flow control to control the flow rate for minimal input power is much more efficient than a system which relies solely on power control. Therefore, the electronic pressure regulator, variable power, external heater, and conical nozzle was chosen as the design variant to pursue.

Key Issues To Be Addressed in Embodiment Design

In the conceptual design phase, crucial specifications of the resistojet system were identified. From these specifications, key issues of the embodiment design phase were identified. Table 4 contains a list of the key issues confronting the resistojet design.

Table 4. Key Issues

Overall understanding of the gas flow through the system
Thrust Control
Integration of pressure, current, and temperature into a single control system
Monitoring of properties necessary for control
Geometry and material selection for each system component
Reduction of heat loss from the heater
Cost and Reliability
Environmental Safety (Plume control and Seals)
Integration of components into the final, complete system

First, an overall understanding of the resistojet is necessary if the effects of the variable tank pressure and gas composition on system performance are to be determined. Due to these variables, one operating mode (i.e. a constant flow rate and input power) can not control the resistojet to within the specified range of instantaneous thrust required. Thus, another key issue is thrust control. To control the thrust, as will be seen in thermal calculations, the gas flow and power input must be controlled. These properties are dependent upon the gas pressure downstream of the electronic pressure regulator, the current to the resistor coil, and the temperature of the gas flowing through the heater. Furthermore, these three values are dependent upon one another, and they must be integrated into a single control system.

By iterating the pressure and nozzle exit Mach number, the calculations are used to determine feasible nozzle and pipe geometries, as well as the flow control requirements, to yield a chosen thrust for a given input power. Also, they determine the operating ranges of the system, allowing material selection issues to be pursued.

How will the control system monitor the fluid properties necessary for thrust control? Devices are necessary to monitor the current flow to the heater, the gas temperature at the heater inlet and outlet, and the pressure downstream of the pressure regulator to allow the control system to adapt. Thermocouples for temperature measurements, and transducers for pressure measurements will be considered.

Another key issue is the geometry and material selection for each of the system components. Geometry selection involves taking iterative steps with initial, arbitrarily selected dimensions until specifications are met, and must be carried out for all components. For example, within the heater, geometries are needed for the resistor coil, the insulating radiation shields, and the gas pipe. Then, with the specified component geometries, and their range of operating conditions (i.e. pressure, temperature, stress, etc.), materials must be selected for each component.

Once materials are found to meet specifications, they should then be chosen for low cost and high reliability, two more key issues facing the resistojet. While no maximum limit is specified, cost is an issue, and is based on materials, manufacturing, operation, and weight as shuttle payload. On the other hand, reliability is specified as a crucial specification. High reliability must be insured by identifying the system's weak points, and then modifying them until system strength is uniform.

Since the external heater was chosen as the heater to pursue, problems with heat loss to the environment are introduced into the system. In fact, the decision to choose the external heater was based on the assumption that this heat loss could be reduced with effective insulation. Questions that need to be resolved include how much insulation is required, what modes of heat transfer are acting, and material selection.

Another issue facing the resistojet is environmental safety. A primary function of the resistojet is to dispose of waste gases produced within the space vessel. Disposing these waste gases involves expanding them into space through the resistojet. Due to the pressure difference between the waste gas and space, some backflow of the exhaust gases will frequently be observed (Figure 2). Some consequences of the waste gas backflow are mass deposition on sensitive surfaces of the vessel, and thermal loading and torques imposed by plume impingement. Fortunately, these problems may be mitigated through careful control of the exhaust flowfield. By confining the exhaust flow field downstream of the resistojet nozzle, the plume is kept away from the vessel, while the maximum thrust is extracted [Carney and Bailey, 1991]. Also, the resistojet system must be sealed against leaks. These seals must be chosen to accommodate the geometry they are sealing, as well as to withstand the system's range of operation at that point.

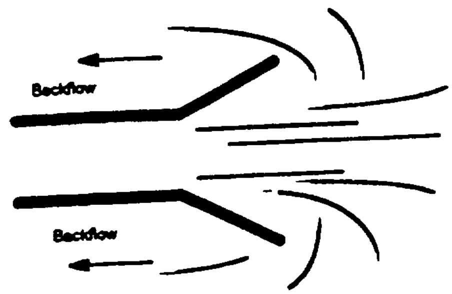


Figure 2. Illustration of Plume Backflow.

Much of the resistojet geometry can be designed more or less independently. However, in the end, all components must be integrated into the complete system, and attached to the existing Space Station. These issues require auxiliary components to be designed, including geometry and material specifications, which must also meet the jet operating requirements.

Means Selected to Address Key Issues

The issue concerning an overall understanding of the thermal system, and how the specified parameters influence the system, will be pursued using an iterative thermal analysis. This analysis will be performed on the extreme cases of 100% composition of each of the five primary waste gases. These extreme cases are chosen to set the resistojet geometry for the specified parameters, and to determine the range of operation. Since the extremes will rarely be encountered, simplifying assumptions were made to facilitate the iterative procedure.

To test the actual performance of the resistojet, experiments should be performed with a prototype. In these experiments, each of the five primary components should be passed through the system in a laboratory controlled vacuum in which thermocouples and pressure transducers are placed at small intervals (~ 1-2 cm) along the resistojet. The gases should be introduced into the system in a relay fashion to test the effect, if any, of the previous gas on the present.

Thrust control will be pursued by controlling the parameters on which thrust is determined. These parameters will be determined by the thermal analysis. Thrust control can also be tested in the vacuum chamber. For example, force output may be measured for several different temperature and pressure settings.

Integration of controllers will involve some software development. The design team recommends the use of a high speed computer for processing pressure and temperature data, and sending appropriate responses to the heater and pressure regulator. Processing and response may be handled by setting up "Virtual Instruments" in the computer software. One software package which may be suited for this is LabVIEW by National Instruments. The virtual instruments constructed should include the formulas used to construct the spreadsheets of Appendix D.

In considering the pressure regulator, before a new design is created, existing systems will be sought. If an existing system conforms to the operating specifications for the resistojet, with or without slight modifications, then that system will be selected. If not, a brief discussion on the adaptation of the pressure regulator for the resistojet will be given.

The heater will be constructed in modules that will be later integrated into a single component. First, the tube in which the propellant flows will be dimensioned to provide efficient heat transfer. Having solved the internal flow problem, the resistor geometry and materials will be selected from energy calculations satisfying average power consumption (125 W). Once again, the resistor design will focus on heat transfer efficiency and reliability. Since radiative heat transfer will occur, radiation shields will be placed around the heater in the most compact configuration to minimize the heat loss to space. The unit will need to be supported by an outer protective sheath sized to withstand operational forces and micrometeorite impact. Auxiliary components will be needed to assemble the tube, shields, and sheath, and to provide attachment points.

The problem of specifying nozzle area ratios to maximize the extraction of energy from the heated waste gases, and to conform to NASA specifications, will be solved with the iterative thermal analysis previously explained. The nozzle geometry will then be completed by choosing a half-angle to minimize flow separation. Also, the issue of material selection will be pursued by considering existing nozzle materials for space applications, and by choosing chemically, mechanically, and thermally compatible material properties with the waste gases and chosen component geometries.

Cost is based on materials, manufacturing, weight, and operation. To estimate material and manufacturing costs, the dimensionally detailed layouts produced and material information must be given to a machine shop. From this information, they must quantify their labor, machining, and welding costs. Also, for a weight cost estimate, the resistojet's total weight must be supplied to NASA, so that an estimate in the respective cost of fuel and space to launch the system. NASA must also give specifications on energy consumption costs in the Space Station for a total resistojet cost to be estimated.

Reliability will be pursued by designing safety factors into each resistojet component, and by choosing components that have extended operating lives in the harsh environment of space.

Evaluation of plume shield performance is largely experimental. Therefore, a recommendation is made to perform an experimental evaluation of the actual plume shield to be used [Carney and Bailey, 1991]. The procedure used by Carney and Bailey [1991] is appropriate for evaluation of the designed plume shield. The experimental evaluation may be performed in an evacuated chamber. Rotary pitot tubes can be used to obtain dynamic pressure and local flow angle. Also, rotary quartz crystal microbalances, which are crystals cryogenically cooled to ter-peratures sufficient to collect mass, can be used to monitor contamination points in space, al .ving :or the mapping of exhaust flowfields. Based on data collected, modifications can be made to optimize the plume shield design [Carney and Bailey, 1991]. Also, for environmental protection, both seals recommended for space propulsion systems and welding processes will be considered to prevent leakage.

Integration of components consists of attaching the components into a complete system, and then attaching the complete system to the Space Station.. Selection will be based on operating range, radiation stability, and corrosion resistance.

Analysis

Thermodynamic Calculations

Based on the NASA specifications, calculations for six different cases of power input and thrust have been pursued. These cases are presented to define the geometry necessary for the specified thrust range of the designed resistojet. Each case represents a different combination of heating and thrust as shown in Table 5.

Table 5. Calculations Case Map

Heating / Thrust	Low (5W)	Medium (125 W)	High (500 W)
Low (0.2 N)	Case 1	Case 2	Case 3
High (1.6 N)	Case 4	Case 5	Case 6

For each of the six cases presented, calculations are given for the five primary waste gases (see Appendix D). This format for presenting the calculations accounts for the extreme cases, thus all the possible combinations of gases which may be produced during flight are within these extreme ranges.

Before the six cases are presented, a set of fixed parameters common to all six cases is given. These fixed parameters include the initial mass if the tank were completely filled, gas enthalpy into and out of the heater, stagnation temperature into and out of the heater (which is assumed equal to static temperature since the Mach number is low), the calculated speed of sound immediately after the heater, pipe dimensions, and the nozzle throat dimensions. Many of these parameters are obtained from calculations based on the given NASA specifications. Other parameters were obtained from the heater design.

Each case was broken into three parts: chosen parameters, iterated parameters, and calculated parameters. After hundreds of iterations of stagnation pressure and nozzle exit mach number, the calculated parameters were matched with the chosen parameters for all cases and each waste gas. The numbers resulting from the iterations deserve some closer attention, as they lend insight into what is happening to the gases in the system.

One important parameter is the area ratio out of the nozzle. This area ratio (nozzle exit area/ nozzle throat area) was set at 2500. The specific throat diameter is 1 mm and the specific nozzle exit diameter is 5 cm. Initially, the area ratio may appear very high when compared to nozzle geometries of typical rockets. Even so, the large area ratio was necessary to obtain temperatures low enough to meet material limitations and provide required thrust. Furthermore, a literature search revealed that other resistojet designs had similar nozzle area ratios.

Another set of parameters which are important are the mass flow rates. The mass flow rates ranged from $3x10^{-5}$ kg/s to $5x10^{-4}$ kg/s. With these flow rates, if the storage tank is full, the discharge times were found to be greater than 10 hours. Though the discharge times were very large, the times could not be reduced due to the strong dependence of this parameter on the limited heater power. Thus, when thrust is not needed, and waste gas must be discharged, the resistojet will operate in the warm gas mode where the waste gas is heated to between 300°C and 500°C.

The calculated exit pressures and exit temperatures ranged from 0.2 Pa to 1.65 Pa and 4° C to 115°C, respectively. These low pressure and temperature ranges are a product of the large nozzle area ratio and high Mach numbers. The low exit pressures and temperatures also indicate that a high percentage of the energy stored in the form of high pressure and temperature was extracted.

Finally, the iterated parameters also deserve consideration. The stagnation pressure, which is approximately equal to the static pressure since velocities are minimal, ranged from 26 kPa to 570 kPa. This low pressure range is well within the limits of the source tank pressure. In contrast, the Mach numbers at the exit tended to be quite high, ranging from 9 to 14. One reason for the high Mach number is the low mass flow rates requiring high exit velocities to achieve the desired thrust levels.

Heater

The function of the heater is to raise the temperature of the waste gases from the storage tank before expanding them through the nozzle. The design team identified five critical specifications for the electrical heater: an average power consumption 1 < 125 W, a peak 2 power consumption of 500 W, a waste gas exit temperature 3 of 1400 °C, and heater 4 attachments at a temperature less than 400 °C. Several other constraints are involved, but the design of the heater will focus on meeting the listed requirements.

The electrical heater for the resistojet will be composed of five major components: the tube, the resistor coil, the insulation, the supports, and the control system. Each part will be addressed in a separate section.

Heater Tube. The heater tube is covered on the outside by the resistor coil, and the waste gases flow inside the tube. This duct is the boundary where heat transfer between the resistor coil and the fluid takes place. Three design concepts were considered for the heater tube: the simple tube, the annulus tube, and the channel tube (Figure 3).

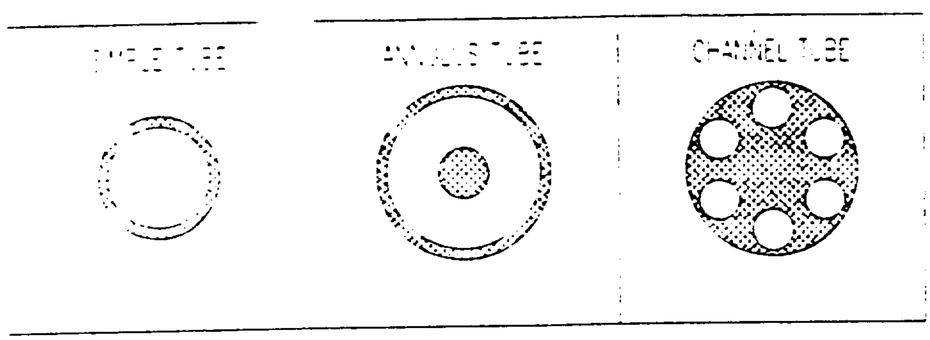


Figure 3. Concept variants for the heater tube.

The annulus tube, although more efficient because of its greater surface area, was not an acceptable design. The annulus was rejected because it required a clearance of less than 2 millimeters between the inner core and the tube to ensure proper mass flow . The best reliability was given by the channel tube with multiple parallel ducts. However, the bulkiness and complex geometry of a channel tube outweighed its advantages. The simple tube was selected because its ease of manufacture and reliability.

After selecting the simple tube, calculations were made to determine the dimensions of the duct. For a given mass flow rate, the diameter of the tube directly influences the flow velocity. Small diameters provide the high flow velocities that are desirable for high thrusts. However, making the diameters too small will create problems with component integration. Alternatively, a large tube diameter will create a slow fluid velocity and increase the component size, requiring more surface insulation and winding material. Calculations of flow velocities and nozzle performance at these velocities showed that the tube diameter should be between 5 and 20 millimeters. The design team proceeded with a tube diameter of 10 millimeters that will yield acceptable flow velocities for the various waste gases considered. This dimension is in agreement with the thermal analysis calculations (Appendix D).

The length of the tube was determined with an energy balance on the propellant within the heater boundary region. Because of preheating caused by the heater element, the waste gases were assumed to enter the tube at a temperature of 77°C, about one hundred degrees Celsius higher than the storage tank temperature [Pugmire et al., 1986]. The problem was further simplified to a tube with constant wall temperature. With an experimental prototype, Pugmire [1986] measured wall temperatures in the heater tube, and recorded the temperature gradients. The result showed that a gradient of only about 100°C exists over a large portion of the heater, and larger gradients are confined to the first few centimeters at the entrance [Pugmire, 1986]. Thus, the constant wall temperature assumption is justified. Using an 80 percent efficiency for heat transfer, the energy balance was applied to the heater. The maximum length required to raise the temperature of the propellants to 1400°C at an average power input of 125 W is:

$$L_t = \frac{\dot{P}_{in} \cdot \eta}{h \cdot \pi \cdot D_{ti} \cdot \Delta T_{LM}} \qquad (1)$$

The design team selected a heater length of 30.0 cm (see Appendix F), which will be able to bring most of the gases to 1400°C at an average power input of 125 W. The wall temperature was kept under a maximum of 1600°C for material limitations

A thickness of 2 millimeters was chosen for the tube. The tube will be threaded to a depth of 1 millimeter to provide guide channels for the resistor coil wire. Material selection for the tube focused on two properties: high thermal conductivity between the coil and tube, and a high melting temperature. Table 6 lists six possible materials. Platinum was chosen because it provides a good combination of the required properties and is readily available in various tube sizes. Furthermore, Platinum is easily machined and corrosion resistant.

Table 6. High temperature metals with high thermal conductivity [Bolz, 1973]

Material	Operating Temperature (°C)	Thermal Conductivity (W / m-K)	Density (g / cm^3)	Comments
Platinum	**1770**	**78.7**	**21.5**	**available**
Thorium	1750	55.0	11.7	radioactive
Tungsten	3400	114	19.3	hard to machine
Zirconium	1850	25.4	6.53	low k
Chromium	1860	60.7	7.2	low k
Molybdenum	2620	104	10.2	oxidizes at 500°C

Resistor Coil. The heater will raise the temperature of the propellant by resistive heating. Current will flow through a coil and heat will be created as dictated by Ohm's law. The rate of heat generation will be proportional to the material resistance and the square of the current magnitude. Coil geometry is important because coil design affects the heater wall temperature distribution.

Three possible options for winding the resistor were considered: helix, double helix, and axial winding (see Figure 4). The axial winding was rejected because it was more difficult to maintain the resistor in close contact with the tubing. The helical winding was selected for its easy assembly, uniform heating at any cross-section, and increasing temperature toward the end of the pipe. However, the simple helical coil poses the problem of having one terminal at each end of the heater. In this configuration the risk of short circuit is increased by running a returning wire inside the heater. Ultimately, the double helix coil was chosen because of its more simple and reliable design.

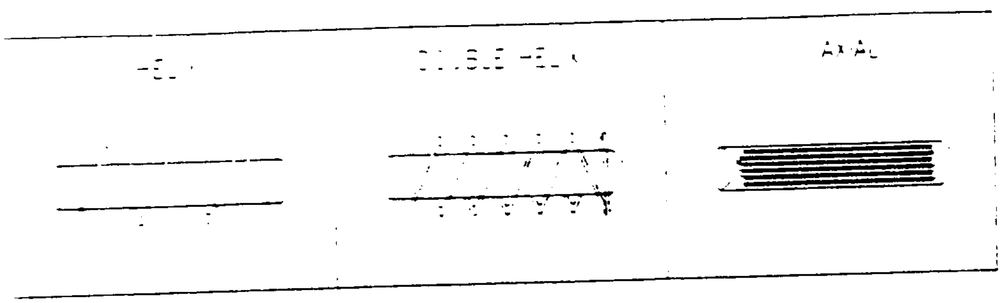


Figure 4. Alternative layouts for the heater resistor coils.

The resistor is a metal wire wound around the heater tube in a double helix configuration, and is designed to dissipate up to 500 W. The current input was limited to 30 Amperes because higher currents would require large wire diameters and would not be compatible with the DC modulated power controller. Calculations showing how the coil length and wire diameter were found are presented in Appendix G.

A list of resistor materials with high melting temperatures was consulted for the wire material selection (see Table 7) [Metal Handbook, 1985]. Tungsten was eliminated because of its poor machinability. Tantalum and platinum were acceptable, but both require insulation from the platinum heater tube to avoid short circuits. Molybdenum was chosen as the wire material because it is readily available in wire form, and its higher conductivity reduces the risk of short circuit.

The wire will be composed of a molybdenum inner core with a platinum coating. This coating will serve as an electrical insulator and a protective shield against oxidation of the

Table 7. High Temperature Materials for Resistor Wire

Material	Operating Temperature (°C)	Resistivity (nΩ-m)	Wire Diameter (mm)	Wire Length (m)	Thermal Expansion (m)
Molybdenum	**1650**	**264**	**1.59**	**4.15**	**0.033**
Tantalum	2500	396	1.82	3.63	N/A
Tungsten	1650	302	1.66	3.97	0.029
Platinum	1650	320	1.69	3.90	0.062

molybdenum. Because the platinum has a coefficient of thermal expansion twice that of the molybdenum wire, the coil must be sized for material dilatation. The solution is to loosely wind the molybdenum wire around the heater, allowing for coil expansion. The necessary gap was found to be 0.5 millimeters per turn of wire.

Power Control. The power controller monitors and adjusts the temperature of the heater to keep the temperature of the exiting propellants at 1400°C. The resistojet will use a dc power controller designed by NASA's R. P. Gruber to fulfill this function. Only minor changes will be necessary to adapt the controller for this specific resistojet design.

In the original controller design, the device senses the heater temperature through thermocouples located at the heater's surface. The controller regulates the power input to the resistor coil to maintain the fluid exit temperature at a preset value. Current signals are generated as pulse-modulated dc power at a frequency of 430 Hz, and delivered at up to 1 kW to a 15Ω load. The electronic circuit includes several MOSFET transistor chips, gate resistors, and zener diodes. The assembled circuit is simple and can be constructed on a small circuit board.

For resistojet integration, the input to the controller will be 150 Volts dc, and the maximum current will be 30 Amperes. This current will be fed into the resistor coil, which has a resistance of about 0.56 Ω. The control unit will use thermocouples to detect the heater temperature at the tube inlet and outlet. This information will feed into the controller unit, which changes the current to accommodate the temperature difference.

The thermocouples chosen to provide temperature feedback information for the heater were type B. This decision was based on the high temperature characteristics of type B thermocouples derived from the platinum-rhodium metallic combination. Type B thermocouples are useful for the temperature range of 0 °C to 1700 °C.

Radiation Shields. An important issue in the design of the resistojet is insulation of the heater section. The lack of an atmosphere outside the tube means that the primary mode of heat loss is through radiation. To minimize heat loss from the heater coil and tube, radiation shields will be designed around the tube to minimize heat loss. Certain characteristics were important in the design, including low material emissivity, low weight and a shield geometry and spacing which permitted only radiative heat transfer. For this resistojet design, a series of materials was considered (see Table 8). Several materials were eliminated from this list on the basis of melting temperature. The shield will be constructed as a material foil that can withstand 1600 ° C near the heater coil. The foil will also have low weight and low emissivity as well.

Table 8. Heater Insulation Materials [Metals Handbook, 1985]

Material	Emissivity	Density (g/cm^3)	Melting Temperature (°C)
Platinum	**.08**	**21.5**	**1770**
Stainless Steel 410	.17	7.8	1500
Aluminum	.04	2.71	650
Nickel	.07	8.9	1453
Gold	.02	19.3	1064
Copper	.05	8.94	1085
Chromium	.24	7.2	1860
Magnesium	.10	1.74	650

On this basis, platinum was chosen as the primary shield material because it offers a very high melting temperature, and a very low emissivity. However, platinum also has a very high density, so stainless steel 410 was chosen as the second material. Stainless steel 410 has a melting temperature of 1500°C, but it also has a lower density, lower cost, and is more durable than the other materials [Callister, 1991].

With an outer sheath diameter of 7.3 cm and a tube outer diameter of 1.4 cm, there will be only 2.95 cm between the tube and sheath. All shields will be constructed as a foil material, with thicknesses of .1 mm for the platinum shields and .15 mm for the stainless steel shields. The foil configuration maximizes the surface area for radiation, reduces weight, and allows more shields to be installed. Also, there will be a spacing of 1.5 mm between each shield, which is ten times the thickness of the thickest shield. To maintain this spacing, several platinum wires of 1.5 mm diameter will be wound around the jet between each shield at several locations along the length of the heater.

Using the available distance and the specified thicknesses, two platinum and 13 stainless steel 410 shields will comprise the radiation shield assembly. The calculations for this procedure are detailed in Appendix I. Platinum shields were minimized because they are heavier and more expensive than the stainless steel shields. In addition, the high melting temperature of the platinum shields are not needed on the outer portion of the jet.

Outer Sheath. In order to protect the inner components and provide structural support, the resistojet must be housed in a sturdy assembly which will protect it from damage inflicted by micrometeorites and vibration. The housing, or sheath, should also have good heat transfer characteristics (i.e. low emissivity). After a search of materials, Iconel X was found to be the best overall choice. Iconel X has a low emissivity (.2), a good combination of toughness and strength, and will not react with any gas components which may reach that surface [Howell, Bannerot and Vliet, 1982].

The dimensions of the outer sheath of the resistojet were determined by heat transfer analysis. By using heat transfer analysis to determine the outer diameter, the effects of heat loss can be controlled, which helps improve the overall efficiency of the resistojet. The heat transfer analysis of the outer sheath is covered in Appendix H. Through this analysis, the inner diameter of the sheath will be 7.3 cm, with a thickness of 0.5 cm. This yields a total diameter of 8.3 cm for the resistojet. The added wall thickness provides a more stable structure for the jet, and does not significantly alter the overall heat transfer characteristics

Mounting Plate. A mounting plate was designed to serve two functions: minimize the amount of conductive heat transfer through the base of the jet and improve structural integrity. To accomplish the first task, a material was needed with low thermal conductivity, as well as good mechanical properties. Sintered alumina (Al_2O_3) was chosen because it has the best combination of modulus of rupture (s_{mr} =200-345 MPa), modulus of elasticity ($E=37 \times 10^4$ MPa), and thermal conductivity (k=30.1 W/m*K) [Schey, 1987].

The mounting plate serves to connect some of the inner components as well. The radiation shields will be attached to the back plate by welding the spacing wire to the plate. Notches in the back of the plate will be designed for alignment of the jet onto the mounting surface, with holes drilled through the outer rib for mounting fasteners. The plate is also designed with connection leads for the heater element, which will also fit into the mounting surface.

Pressure Regulator

The pressure regulator used in the resistojet is one of the primary components of the entire system. This component allows the resistojet to achieve the demanded thrust levels, while mitigating the severe (possibly high frequency) loading of the heater. Therefore, a more detailed discussion on this important component is justified.

The function of a pressure regulator is to reduce the pressure of a high pressure source to a prescribed lower pressure. Essentially, this device allows for the controlled extraction of energy from an energy source. In the resistojet, an electronic pressure regulator was chosen based on the need for dynamic, perhaps, continuous control of the waste gas pressure during firing of the jet. An electronic pressure regulator is actuated electromagnetically using solenoids. The regulator chosen for the resistojet electronic regulator is a pressure regulating valve [Lansky and Schraeder, 1986].

The pressure regulating valve operates by monitoring the downstream pressure. In the resistojet system, a pressure transducer will be employed to monitor this pressure. Appendix E describes the selection of this transducer. In response to the desired downstream pressure set by the control system, the throttling of the valve is adjusted as necessary. The throttling configuration for the resistojet is a simple one, consisting of a spring, a piston, and a cylinder. Downstream of the regulating valve, some of the gas will be bled into the cylinder. In response to the pressure of this gas, the piston will rise or fall, the level being determined by a spring which pushes the piston against the cylinder pressure. Thus, the downstream pressure is set by the compressive force of the spring, which is determined by the spring constant and the level of initial spring compression. The compressive force exerted by this spring is controlled by the solenoid, which, in turn, is controlled by the integrated control system. As the piston rises, a needle valve attached to the piston will rise and start to close, reducing the pressure. If the piston falls, the valve will fall and open, increasing pressure until the desired level for resistojet operation is reached [Lansky and Shraeder, 1986].

The force required by the solenoid to shift the high pressure differential valve may be high. Thus, a large solenoid with a high inrush current demand is necessary. An alternating current solenoid is selected because it can operate at high inrush, while maintaining low holding current levels. This results in low power consumption [Lansky and Shraeder, 1986].

Material selection for the electronic pressure regulator housing and pipe fittings is again based on the need for similar thermal coefficients of expansion to prohibit the introduction of excessive shear stresses on the seals. Thus, to compare with the gas pipe, platinum is chosen for the housing and gas pipe fittings. Material selection for internal components (i.e. spring, needle valve, piston) is based on corrosion resistance, strength, and non-reactiveness with the waste gases. As explained with the seals, stainless steel is chosen for the regulator internal components.

Specific calculations determining the pressure regulating valve have not been done due to time limitations. If time permitted, the following calculation to size the pressure regulator would be pursued. Regulator sizing is based on providing the downstream flow rate, where:

$$\text{flow rate}\left[\mathrm{m^3/s}\right] = \frac{V\left[\mathrm{m^3}\right]\cdot\text{compression ratio}}{\text{time to fill cylinder}\left[\mathrm{s}\right]} \tag{2}$$

Flow Control. For control, the system is a closed loop system. The microprocessor receives the transducer signal, compares it to a desired set point, determined by what thrust and input power levels are desired and by what gas composition is passing through the system, and sends a feedback signal to the solenoid to exert the required compression force on the spring. With a microprocessor, response time is dependent upon the amount of time needed to fill and compress, or vent and decompress the cylinder volume under pressure control [Lansky and Schrader, 1986]. Thus, Equation (2) also affects flow control time response.

Nozzle

Though the area ratio is a determining factor in the performance of the nozzle, it is not the only significant parameter. The calculations leading to the designed nozzle area ratio were based on steady state flow assumptions. The validity of the steady state flow assumption is largely determined by the nozzle half-angle, θ (see Figure 5) [Hill and Peterson, 1992].

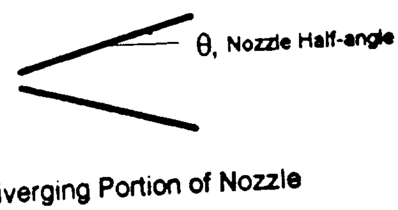


Figure 5. Nozzle Half-angle.

Given a fixed nozzle area ratio, the length of the nozzle and the rate of change in nozzle area are governed by the nozzle half-angle. If the rate of change in nozzle area is too great, flow separation may be encountered in the nozzle. The net result would be a drop in thrust produced and an increase in pressure and temperature [Hill and Peterson, 1992].

Hill and Peterson [1992] offer the following relation for determining the percentage of ideal thrust, %T, obtained given a nozzle half-angle,θ:

$$\%T = 0.5\,(1 + \cos\theta) \qquad (3)$$

If we confine our consideration of percentage of ideal thrust to greater than 90%, this relation states that the maximum nozzle half-angle allowable is 37°. Equation (3) also implies that a nozzle half-angle of 0° (or an infinitely long nozzle) is necessary to achieve ideal thrust. A trade off between nozzle length and thrust must be made. The nozzle half-angle chosen in the design was 25°, allowing for up to 95% of ideal thrust. This angle was considered a fair compromise for thrust and geometry.

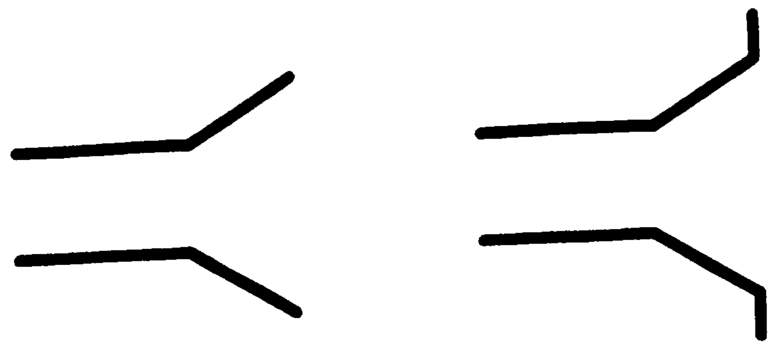
The nozzle geometry was already defined in the conceptual design of the resistojet. The specific dimensions for the nozzle include a 25° half-angle, area ratio of 100 into the nozzle, area ratio of 2500 out of the nozzle, and throat diameter of 1 mm.

The selection of materials for the nozzle must receive considerable attention because of the very harsh environmental conditions. During operation, the nozzle material must resist extreme temperatures in the range of 4°C to 1500°C. Furthermore, the nozzle internal surface must be chemically compatible with the exiting propellants to avoid corrosion. Mechanical properties are also very important for abrasion resistance against gases exiting at high velocities, and possible shock waves. Finally, to avoid interconnection failures and fluid leaks, the nozzle material must have a coefficient of thermal expansion close to that of the heater tube material, namely platinum.

Several commonly used nozzle materials were considered for the resistojet application. For example, graphite has excellent properties at high temperatures up to 3000°C and has low density of 2.25 grams/cm^3, but it was eliminated because of its weakness at low temperatures. Metallic oxides and carbides are developed for high temperature application but they were not chosen because they are brittle and difficult to manufacture [Wolff, 1962]. Finally, refractory metals offer good mechanical properties in the temperature range of interest. The best among these metals are tungsten, tantalum, and molybdenum. Except for tungsten which is difficult to machine, tantalum and molybdenum meet the specifications. However, the use of these two material would reduce the reliability of the heater tube and nozzle connection because the coefficient of thermal expansion for these two materials is about half that of platinum [Handbook of Metals, 1973]. Platinum was selected at last in an effort to increase the resistojet reliability. This material meets the requirements in terms of good thermal and mechanical properties, coefficient of thermal expansion, and also good thermal conductivity that will help in heat dissipation. The high temperature properties of platinum can further be improved by alloying, thus grain stabilized platinum was chosen for the resistojet nozzle [Morren, 1986].

Plume Shield

Control of the exhaust flow field may be achieved through the use of plume shields. Two types of plume shields appear in Figure 6. Carney and Bailey [1991] performed an experimental evaluation of these two plume shield configurations. The first configuration is a simple conical plume shield (see Figure 6a). The second configuration is a variation of the first. The second plume shield studied is a conical plume shield with an annular plate placed at the exit plane (see Figure 6b).



A Simple Conical Plume Shield

B Conical Plume Shield with annular plate

Figure 6. Alternative Plume Shields

Carney and Bailey [1991] found that the conical plume shield with an annular plate at the exit plane was more effective in controlling the exhaust flowfield. Though the simple conical plume shield limited backflow to roughly 0.2% of the total resistojet mass flow, the addition of the annular plate further reduced the amount of backflow by a factor of 2. Over the lifetime of the resistojet, mass deposition may be reduced from 7 kg to 3.5 kg [Carney and Bailey, 1991].

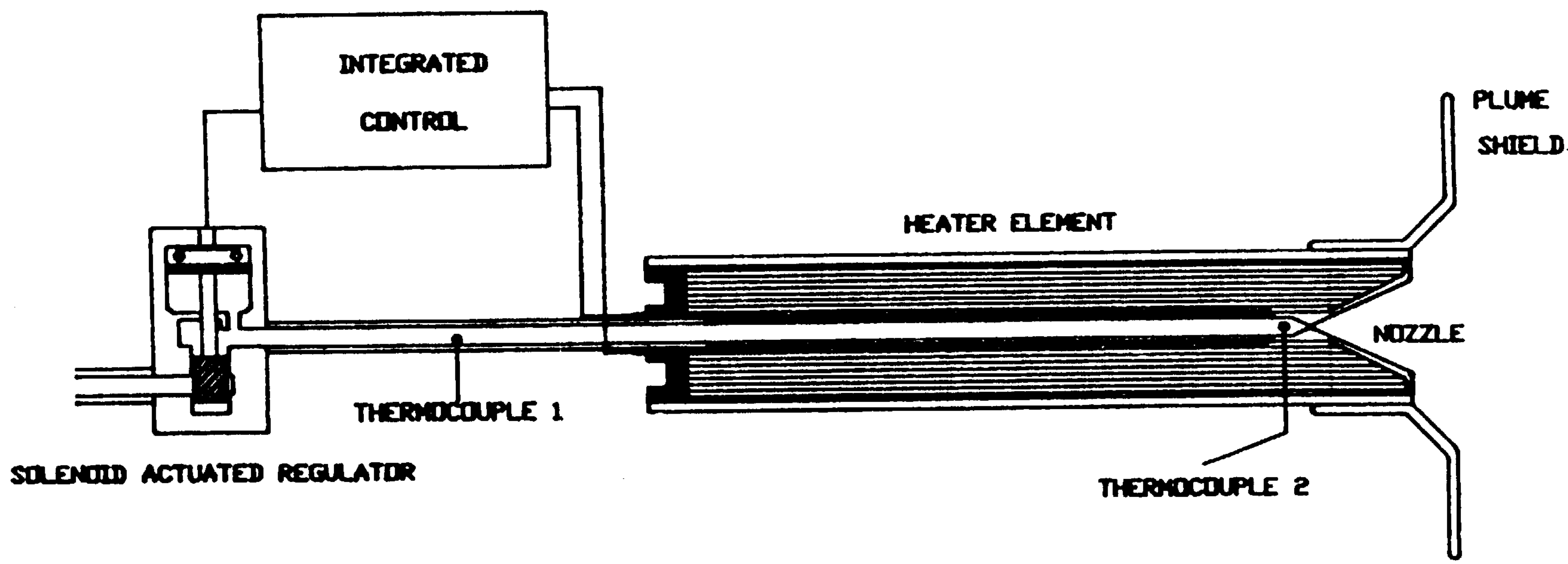
Based on the work done by Carney and Bailey [1991], a decision was made to include the conical plume shield with the annular plate in our design. Admittedly, the annular plate configuration does not offer a significant advantage over the simple conical configuration. However, the addition of the annular plate is neither costly nor imposes excessive weight to the design.

Components Integration

To complete the final resistojet, the individual components must be integrated while paying considerable attention to mechanical connections and electronic control. First, the mechanical parts are assembled focusing on function sharing. Once the assembly completed, the electronic control loop is laid out.

The heater is constructed starting with the resistor wire wound in a double helix around the platinum tube. Then, the nozzle and the mounting plate are diffusion bonded to the heater tube and sealed against propellant leakage. Radiation shields are wrapped around the resistor coil using small wire inserts to insure the correct spacing. Before placing the outer sheath, one of the thermocouples needs to be placed between the heater tube and the nozzle. The complete heater unit will then be attached to the outer sheath, the ceramic plate will be bolted, and the nozzle welded by diffusion. The last assembly on the heater requires the plume shield to be bolted to the end of the resistojet. The mechanical integration is completed with the pressure regulator placed upstream from the heater on another extension pipe. For good thermal coupling

ASSEMBLED RESISTOJET



Note: Pressure Regulator Enlarged to show details and mechanical compatibility, this pipe has the same inside and outside diameter as the heater pipe and is also made of platinum. The pipe will need to be at least 20 cm long to limit temperature contamination of the pressure regulator. Therefore, the exact length is adjustable to fit spacecraft configurations. Immediately before the heater inlet, the second thermocouple is fixed on the same pipe. A more thorough treatment of the seals appears in Appendix J.

Because they are small units, the power and pressure controller will be placed inside the spacecraft where they will receive the input signal required for operation. These components are electronic circuits that can interface with an onboard computer. As designed, the resistojet requires two input signals. First, the pressure regulator, which functions as a modulated valve, adjusts to the signal carrying the information that turns the resistojet "on" or "off". The second input will tell the system whether thrust is required or not.

After receiving the two operating signals, the resistojet becomes a self-sufficient device. The output from the two thermocouple are fed to a central processing unit. This microprocessor adjusts the power in the resistor and the upstream pressure as to keep the propellant to a specified temperature and to maintain required thrust.

Conclusion

Based on the specifications set forth by NASA in their effort to find a system which could counter the detrimental effects of atmospheric drag on the Space Station's orbit, and simultaneously exhaust waste gases produced on the station in a safe and environmentally conscious manner, this paper presented the embodiment design phase of an electrically powered resistojet. The resistojet was pursued as a result of its extended operating life, multipropellant capability, reliability, and ability to control exhaust emissions.

First, a summary of the conceptual design phase, including the specifications, the functional analysis, the investigation and elimination of feasible resistojet design variants, and the selection of a concept through a decision matrix was presented to provide the reader with requirements of, and objectives for, the embodiment design. Basically, the resistojet was designed for fine thrust control, efficient use of available power, reliable operation, and minimal cost. The electronic pressure regulator, variable power control, external heater, and conical nozzle concepts were selected as the designs to pursue because they provided superior thrust control and efficiency.

With these design objectives, and the limiting specifications, key issues to be pursued with the chosen concept were identified and researched. To solve many of these issues, an iterative approach was taken with the thermal operation of the resistojet. This thermal analysis allowed the component geometries and operating parameters for every possible waste gas composition, required thrust output, and available power input to be determined. Then, based on these parameters, material selection for each of the primary resistojet components was researched, and a single material was chosen for the nozzle, heater tube, pipe, and pressure regulator pipe fittings to allow for a common thermal expansion for the components directly contacting the waste gas flow. This was done to maintain mechanical integrity, and to prevent environmental contamination from seal or weld rupture.

After designing the primary resistojet components, it became apparent that several auxiliary components were needed for a final assembly and for integration with the Space Station. Both the geometry and material properties of these auxiliary components were chosen to mesh with the existing design. Also, some manner of seal or weld was necessary to make the resistojet a closed loop system, and to prevent leakage. Therefore, the method and material selection for leak protection was based on performance in the harsh space environment, and high mechanical integrity.

Prototype testing of the resistojet system is recommended as the next step in the design of the resistojet. Several experimental procedures were defined, such as plume shield and thrust control testing. In the thermal analysis presented, many simplifying assumptions were made, since only the general range of operation of the resistojet was desired. To account for the difference between ideal and real conditions, experiments must be performed. After prototype testing, and the pursuit of any necessary concept modifications, proceeding with the detailed design phase is recommended.

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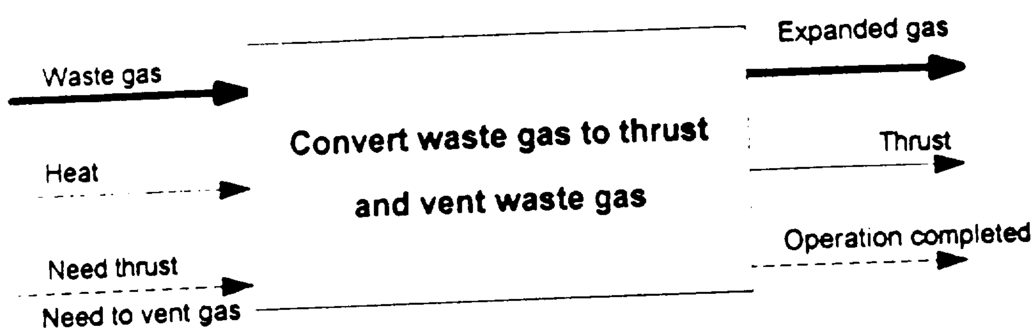
Appendix A
Full Specification List

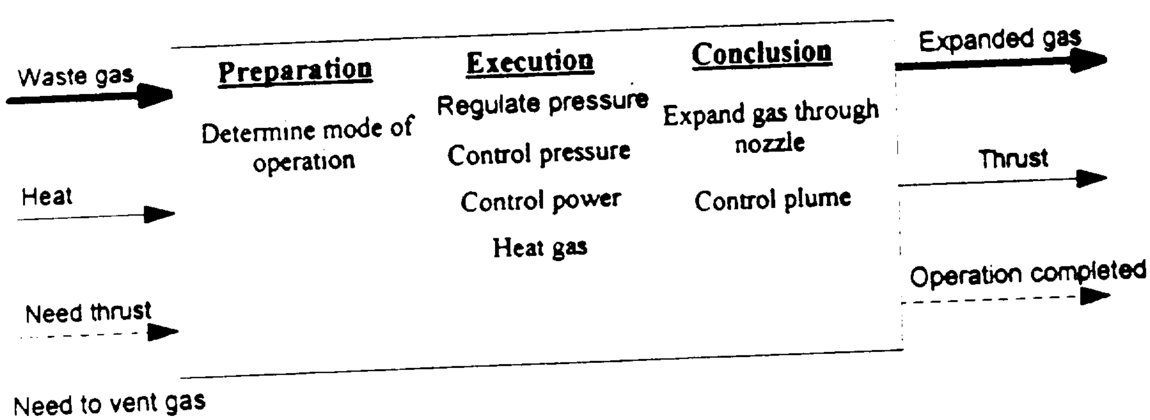
D/W	Requirements
	1. Forces:
D	Generate 50-350 millipounds of instantaneous thrust
W	Weight < 20 lbs on Earth (equivalent to 9 kg of mass)
D	Withstand shuttle launch forces and vibrations of 3.3 sustained G's
D	Withstand micrometeorite impact
	2. Energy:
D	Withstand inlet gas pressure of 80-1000 psia
D	Heat gases from -1 C to 1400 C for discharge
D	Operate with peak power input of 500 W and average power < 125 W
D	Seals must withstand temp. and pressure operating ranges (1.5 safety factor)
D	Impulse over life of operation = $2x10^6$ lbf*sec
	3. Material:
D	Withstand temperature ranges of operation
D	Withstand pressure ranges of operation
D	Must not off-gas in a vacuum
D	Must not react with waste gases
	4. Signals:
D	Outputs: Change in gas temperature needed Change in the current to the heater Change in pressure needed downstream of the pressure regulator
D	Inputs: Instantaeous gas temperature in the heater Instantaneous current to the heater Instantaneous pressure downstream of the pressure regulator
D	Minimal response time
	5. Safety:
W	Emergency system stop
	6. Operation:
D	Must accomodate multiple propellents: H_2O, N_2, Air,Ar, CO_2
D	Must have life of 10,000 hrs, or 10,000 cycles over 18 years
D	Must operate in zero gravity

Appendix B
Functional Analysis

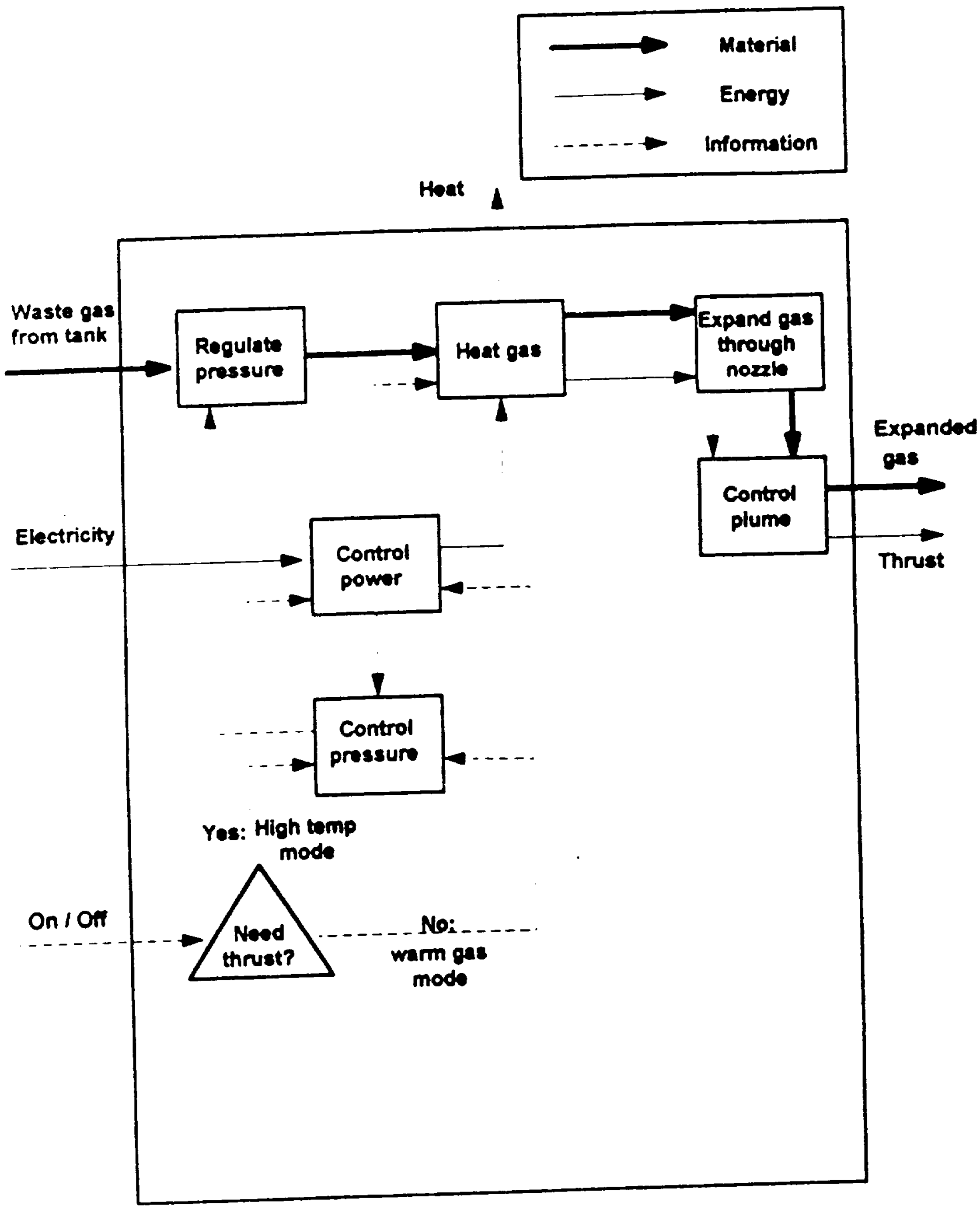
Black Box Description



Process Description



Function Structure



Function Structure Justification

The function structure of the resistojet is divided into three flows. For the material flow, waste gas from the tank first goes through the pressure regulator and into the heater. The waste gas will be heated in the heater to the temperature needed, depending on what mode is required (i.e. high temperature or warm gas), and then expanded into space through the nozzle. Once the heated gas leaves the nozzle, the plume will be controlled to prevent any interference with any payload viewing function and to prevent any environmental contamination.

Electricity is the main source of energy for the resistojet. Electricity will provide energy to the power control, the pressure control, and the heater. In the heater, there will be some energy losses due to radiation . Also, energy will exit the system in the form of heat and mechanical energy.

The initial signal for the information flow is a signal from the tank indicating that the waste gas needs venting. If thrust is needed, the resistojet will operate in the high temperature mode and heat the waste gas to about 1400°C. If thrust is not needed, the resistojet will operate in the warm gas mode where the waste gas will be heated to between 300°C and 500°C. Separate signals will be sent to the pressure and power controls to set the appropriate levels. The pressure control will then send a signal to the pressure regulator to control the incoming waste gas, while the power control will send a signal to the heater to control the temperature. These signals must be integrated into a single controller because of their interdependance.

Appendix C

Decision Matrix Rating Factors and Weightings

Thrust control was given the highest weighting of thirty-five percent because it defines the operation of the system. That is, given the specification list, the resistojet geometry, dimensions, control system, and material limitations are all based on the necessity to control the thrust within the specified parameters. Once the system parameters are defined, the system is designed for efficiency and reliability. Therefore, they were given equal weights of twenty-seven percent. Efficiency is important due to the limited power resources available on the station, whereas reliabilty was defined by NASA as a crucial specification. Cost was given the least weight (eleven percent) because a maximum limit was not quantitatively specified. However, cost is important, as with any design, for economical reasons.

In a decision matrix, each design was rated on a scale of five to ten for each concept rating factor, where a ten is the best possible design, and a five is acceptable. A scale with a larger range was considered, but deemed unneccesary since all designs considered in the decision matrix are acceptable. From the decision matrix, two designs, the mechanical and electronic pressure regulators with variable power control, external heating, and a conical nozzle are chosen.

Appendix D
Thermal Analysis

Equation List for the Thermal Analysis

$$q = \dot{m}[H + v^2/2g_c]_{in} = \dot{m}[H + v^2/g_c]_{out} \qquad \text{equation 1}$$

$$\hat{c} = P/RT \qquad \text{equation 2}$$

$$\dot{m} = \partial vA \qquad \text{equation 3}$$

$$Mach = v/c \qquad \text{equation 4}$$

$$c = \gamma RT \qquad \text{equation 5}$$

$$\frac{A}{A_{throat}} = [1/M]\left[[2/[\gamma+1]]\left[1+[[\gamma-1]/2]M^2\right]^{[[\gamma+1]/[2[\gamma-1]]]}\right] \qquad \text{equation 6}$$

$$\frac{P_0}{P} = \left[1+[[\gamma+1]/2]M^2\right]^{[\gamma/[\gamma-1]]} \qquad \text{equation 7}$$

$$T = \dot{m}v_{exit} + P_{exit}A_{exit} \qquad \text{equation 8}$$

Equations one through seven are found in Saad's Compressible Fluid Mechanics book [1993], and equation eight is taken from Hill and Peterson's Mechanics and Thermodynamics of Propulsion book [1989].

An important key issue concerning the design of the resistojet is an understanding of the fluid flow through the resistojet system. The most crucial specifications governing the dynamics of this flow of were supplied by NASA. With the given values listed on the dimensional analysis, these specifications include the power available to the heater, the required thrust for each resistojet, the operating life for each resistojet, the storage tank pressure and temperature, the heater inlet and outlet temperatures, and the waste gas composition.

Thermodynamic Assumptions:

Inviscid Flow	Isothermal Tank Discharge
Ideal Gas	Ideal Nozzle
Constant Specific Heats	Heater is 80% Efficient
Neglect Major, Minor Head Loss	Gas is Steady Flow and Steady State
Isentropic Flow	One-Dimensional Flow
Heating is a Constant Pressure Process	

Calculations were performed based on these defining specifications, as well as on several fixed parameters. Firstly, the heater was considered. Since the inlet and outlet temperatures of the heater are fixed, by assuming ideal gases, we see that the inlet and outlet enthalpies are dependent only on waste gas composition, and can be found from thermodynamic ideal gas tables. By writing an energy balance for the heater, shown in equation 1, we can compute the gas mass flow rate by choosing an inlet power to the heater. This energy balance assumes the gas is steady with respect to flow and state. Kinetic energy terms are present in the energy balance; however, we assume that their influence on the mass flow rate is negligible.

Was the assumption that the heater inlet and outlet velocities had a negligible effect on the mass flow valid? By arbitrarily selecting the gas pressure, where we assume the heating to be a constant pressure process, the density of the waste at the heater inlet and outlet can be calculated from the ideal gas law, shown as equation 2. Then, from these densities, the inlet and outlet velocities can be calculated from the continuity equation, shown as equation 3. As seen on the dimensional analysis, the velocities are very small. Thus, our assumption introduces less than 0.1 percent error. good

At the heater outlet, the Mach number can be calculated from the outlet fluid velocity and temperature by using the definitions of Mach number and the speed of sound, shown as equations 4 and 5, respectively. Then, at this point, an initial nozzle geometry was assumed. For isentropic flow, equation 6 relates nozzle area ratios (i.e. the area at any point in the nozzle over the throat area) to the Mach number at that point, and the ratio of specific heats [Saad, 1993]. Therefore, at the nozzle inlet, the inlet area ratio can be calculated. Initially, this calculated inlet area ratio does not agree with the assumed area ratio. However, by iterating the arbitrarily selected pressure, the fluid density is changed. In turn, the flow velocity is changed, which changes the Mach number until the calculated and assumed inlet area ratios agree.

Similarly, by assuming a nozzle exit Mach number, equation 6 can be used to calculate the nozzle outlet area ratio. Then, the initial Mach number can be iterated so that the assumed and calculated exit area ratios compare. From the nozzle exit Mach number, the nozzle exit pressure ratio can be calculated using another isentropic flow property relation, shown as equation 7. Here, since the flow is isentropic, no shock occurs, and assuming an inviscid fluid, the stagnation pressure is constant throughout the nozzle. Also, since the fluid velocity in the pipe has a very small Mach number, this stagnation pressure approximately equals the static pressure in the pipe. Finally, choosing a value for thrust, the nozzle exit velocity can be found from equation 8. Then, by the definition of Mach number, the nozzle exit temperature can be calculated.

By iterating the pressure and nozzle exit Mach number, these calculations are used to determine feasible nozzle and pipe geometries, as well as the mass/pressure control requirements, to yield a chosen thrust for a given input power. Also, they determine the operating ranges of the system, allowing material selection issues to be pursued.

NASA Specifications:					
power available [kW]	0 05 to 0 400				
thrust [N]	0 2 to 1 6				
operating life [h]	10.000				
tank pressure [kPa]	552 to 6895				
tank temperature [K]	272				
heater entrance temperature [K]	272				
heater exit temperature[K]	1673				
waste gases available:	spc. heat ratios:	gas constants:			
air	1.4	287 J/kg*K			
argon	1.667	208.13 J/kg*K			
carbon dioxide	1.288	188.92 J/kg*K			
nitrogen	1.4	296.8 J/kg*K			
water vapor	1.329	461.52 J/kg*K			
Calculations:					
	air	*argon*	*carbon dioxide*	*nitrogen*	*water vapor*
fixed parameters:					
initial mass [kg]	15	20.7	22.8	14.5	9.33
enthalpy into heater [kJ/kg]	273.92	142.22	192.15	283.99	503.22
enthalpy out of heater [kJ/kg]	1848.2	871.17	1847.6	1898.8	3683.1
stagnation temperature in heater [K]	272	272	272	272	272
stagnation temperature out heater [K]	1673	1673	1673	1673	1673
gas constant [J/kg*K]	287	208.13	188.92	296.8	461.52
specific heat ratio	1.4	1.667	1.288	1.4	1.329
speed of sound out heater [m/s]	819.8849919	761.8739291	638.0355398	833.7655306	1012.99132
operating life [h]	10000	10000	10000	10000	10000
pipe diameter [m]	0.01	0.01	0.01	0.01	0.01
pipe area [m^2]	7.85E-05	7.85E-05	7.85E-05	7.85E-05	7.85E-05
throat diameter [m]	0.001	0.001	0.001	0.001	0.001
throat area [m^2]	7.85E-07	7.85E-07	7.85E-07	7.85E-07	7.85E-07

Case 1: Q= 0.05 kW & T=0 2 N					
chosen parameters:					
heater power [kW]	0 05	0.05	0 05	0 05	0 05
thrust [N]	0.2	0.2	0 2	0 2	0.2
area ratio into nozzle	100	100	100	100	100
area ratio out of nozzle	2500	2500	2500	2500	2500
nozzle exit area [m^2]	0.001963496	0.001963496	0.001963496	0.001963496	0.001963496
iterated parameters:					
stagnation pressure [Pa]	40910	70940	32500	40560	26160
nozzle exit mach no.	13.79	34 18	9 69	13.79	11
calculated parameters:					
gas density in heater [kg/m^3]	0.524057184	1.253105384	0.632465033	0.502417948	0.208390689
gas density out heater [kg/m^3]	0.085202363	0.203732615	0.102827549	0.081684209	0.033880614
mass flow rate [kg/s]	3.17606E-05	6.85918E-05	3.02033E-05	3.09634E-05	1.57239E-05
estimated discharge time [h]	131.19	83.82925	209.6903333	130.0819167	164.82378
flow velocity in heater [m/s]	0.771648326	0.696938954	0.608033471	0.784681655	0.960707175
flow velocity out heater [m/s]	4.746204592	4.286687019	3.739852929	4.826369148	5.909055528
mach no. out of heater	0.005788866	0.005626504	0.005861512	0.005788641	0.005833274
area ratio into nozzle	99.97041052	99.97194957	99.98105816	99.97430503	99.99876063
nozzle exit velocity [m/s]	6290.324703	2915.123656	6608.387319	6452.329391	12704.36506
nozzle exit area [m^2]	0.001960071	0.001963311	0.001960641	0.001960071	0.001961564
nozzle exit pressure ratio	2.69151E-06	3.33089E-07	6.35753E-06	2.69151E-06	4.6438E-06
nozzle exit pressure [Pa]	0.110109484	0.02362931	0.206619612	0.109167457	0.121481759
nozzle exit temperature [C]	42.86136641	4.282947481	115.2121463	42.86136641	80.03061542

Case 2: Q= 0.125 kW & T=0.2 N					
chosen parameters:					
heater power [kW]	0.125	0.125	0.125	0.125	0.125
thrust [N]	0.2	0.2	0.2	0.2	0.2
area ratio into nozzle	100	100	100	100	100
area ratio out of nozzle	2500	2500	2500	2500	2500
exit area [m^2]	0.001963496	0.001963496	0.001963496	0.001963496	0.001963496
iterated parameters:					
stagnation pressure [Pa]	102280	177350	81250	101400	65390
nozzle exit mach no.	13.79	34.18	9.69	13.79	11
calculated parameters:					
gas density in heater [kg/m^3]	1.31020701	3.132763459	1.581162584	1.256044871	0.520897061
gas density out heater [kg/m^3]	0.213016322	0.509331537	0.257068872	0.204210523	0.084688584
mass flow rate [kg/s]	7.94014E-05	0.00017148	7.5508[illegible]-05	7.74085E-05	3.93097E-05
estimated discharge time [h]	52.476	33.5317	83.87613333	52.03276667	65.929512
flow velocity in heater [m/s]	0.771610603	0.696938954	0.608033471	0.784681655	0.960854095
flow velocity out heater [m/s]	4.745972572	4.286687019	3.739852929	4.826369148	5.909959192
mach no. out of heater	0.005788583	0.005626504	0.005861512	0.005788641	0.005834166
area ratio into nozzle	99.97529766	99.97194957	99.98105816	99.97430503	99.98347091
nozzle exit velocity [m/s]	2512.052371	1165.643656	2635.307319	2576.785391	5072.655379
nozzle exit area [m^2]	0.001960071	0.001963311	0.001960641	0.001960071	0.001961564
nozzle exit pressure ratio	2.69151E-06	3.33089E-07	6.35753E-06	2.69151E-06	4.6438E-06
nozzle exit pressure [Pa]	0.275287168	0.059073276	0.51654903	0.272918644	0.30365796
nozzle exit temperature [C]	42.86136641	4.282947481	115.2121463	42.86136641	80.03061542

Case 3 Q= 0.4 kW & T=0.2 N					
chosen parameters					
heater power [kW]	0.4	0.4	0.4	0.4	0.4
thrust [N]	0.2	0.2	0.2	0.2	0.2
area ratio into nozzle	100	100	100	100	100
area ratio out of nozzle	2500	2500	2500	2500	2500
nozzle exit area [m^2]	0.001963496	0.001963496	0.001963496	0.001963496	0.001963496
iterated parameters:					
stagnation pressure [Pa]	327280	567500	259980	324470	209230
nozzle exit mach no.	13.79	34.18	9.69	13.79	11
calculated parameters:					
gas density in heater [kg/m^3]	4.192457471	10.02448978	5.059331058	4.019219716	1.666727208
gas density out heater [kg/m^3]	0.681618907	1.62980348	0.822557112	0.653453534	0.270980156
mass flow rate [kg/s]	0.000254084	0.000548734	0.000241626	0.000247707	0.000125791
estimated discharge time [h]	16.39875	10.47865625	26.21129167	16.26023958	20.6029725
flow velocity in heater [m/s]	0.771648326	0.696963515	0.608080246	0.784705838	0.960936757
flow velocity out heater [m/s]	4.746204592	4.286838092	3.740140632	4.826517894	5.910467624
mach no. out of heater	0.005788866	0.005626703	0.005861963	0.005788819	0.005834668
area ratio into nozzle	99.97041052	99.9684266	99.97336761	99.97122409	99.97487044
nozzle exit velocity [m/s]	780.3447035	363.7986795	814.313351	800.4946038	1574.788682
nozzle exit area [m^2]	0.001960071	0.001963311	0.001960641	0.001960071	0.001961564
nozzle exit pressure ratio	2.69151E-06	3.33089E-07	6.35753E-06	2.69151E-06	4.6438E-06
nozzle exit pressure [Pa]	0.880875874	0.189027822	1.652829745	0.873312744	0.971621884
nozzle exit temperature [C]	42.86136641	4.282947481	115.2121463	42.86136641	80.03061542

Case 4: Q= 0.05 kW & T=1.6 N					
chosen parameters:					
heater power [kW]	0.05	0.05	0.05	0.05	0.05
thrust [N]	1.6	1.6	1.6	1.6	1.6
...atio into nozzle	100	100	100	100	100
... ratio out of nozzle	2500	2500	2500	2500	2500
nozzle exit area [m^2]	0.001963496	0.001963496	0.001963496	0.001963496	0.001963496
iterated parameters:					
stagnation pressure [Pa]	40910	70940	32500	40560	26160
nozzle exit mach no.	13.79	34.18	9.69	13.79	11
calculated parameters:					
gas density in heater [kg/m^3]	0.524057184	1.253105384	0.632465033	0.502417948	0.208390689
gas density out heater [kg/m^3]	0.085202363	0.203732615	0.102827549	0.081684209	0.033880614
mass flow rate [kg/s]	3.17606E-05	6.85918E-05	3.02033E-05	3.09634E-05	1.57239E-05
estimated discharge time [h]	131.19	83 [illegible]	209.6903333	130.0819167	164.82378
flow velocity in heater [m/s]	0.771648326	0.69693[illegible]	0.608033471	0.784681655	0.960707175
flow velocity out heater [m/s]	4.746204592	4.286687019	3.739852929	4.826369148	5.909055528
mach no. out of heater	0.005788866	0.005626504	0.005861512	0.005788641	0.005833274
area ratio into nozzle	99.97041052	99.97194957	99.98105816	99.97430503	99.99876063
nozzle exit velocity [m/s]	50370.1647	23325.72366	52960.98732	51667.00939	101741.0051
nozzle exit area [m^2]	0.001960071	0.001963311	0.001960641	0.001960071	0.001961564
nozzle exit pressure ratio	2.69151E-06	3.33089E-07	6.35753E-06	2.69151E-06	4.6438E-06
nozzle exit pressure [Pa]	0.110109484	0.02362931	0.206619612	0.109167457	0.121481759
nozzle exit temperature [C]	42.86136641	4.282947481	115.2121463	42.86136641	80.03061542

Case 5: Q= 0.125 kW & T=1.6 N					
chosen parameters:					
heater power [kW]	0.125	0.125	0.125	0.125	0.125
thrust [N]	1.6	1.6	1.6	1.6	1.6
area ratio into nozzle	100	100	100	100	100
area ratio out of nozzle	2500	2500	2500	2500	2500
nozzle exit area [m^2]	0.001963496	0.001963496	0.001963496	0.001963496	0.001963496
iterated parameters:					
stagnation pressure [Pa]	102280	177350	81250	101400	65390
nozzle exit mach no.	13.79	34.18	9.69	13.79	11
calculated parameters:					
gas density in heater [kg/m^3]	1.31020701	3.132763459	1.581162584	1.256044871	0.520897061
gas density out heater [kg/m^3]	0.213016322	0.509331537	0.257068872	0.204210523	0.084688584
mass flow rate [kg/s]	7.94014E-05	0.00017148	7.55082E-05	7.74085E-05	3.93097E-05
estimated discharge time [h]	52.476	33.5317	83.87613333	52.03276667	65.929512
flow velocity in heater [m/s]	0.771610603	0.696938954	0.608033471	0.784681655	0.960854095
flow velocity out heater [m/s]	4.745972572	4.286687019	3.739852929	4.826369148	5.909959192
mach no. out of heater	0.005788583	0.005626504	0.005861512	0.005788641	0.005834166
area ratio into nozzle	99.97529766	99.97194957	99.98105816	99.97430503	99.98347091
nozzle exit velocity [m/s]	20143.98837	9329.883656	21176.34732	20662.65739	40687.31138
nozzle exit area [m^2]	0.001960071	0.001963311	0.001960641	0.001960071	0.001961564
nozzle exit pressure ratio	2.69151E-06	3.33089E-07	6.35753E-06	2.69151E-06	4.6438E-06
nozzle exit pressure [Pa]	0.275287168	0.059073276	0.51654903	0.272918644	0.30365796
nozzle exit temperature [C]	42.86136641	4.282947481	115.2121463	42.86136641	80.03061542

Case 6: Q= 0.4 kW & T=1.6 N					
chosen parameters:					
heater power [kW]	0.4	0.4	0.4	0.4	0.4
thrust [N]	1.6	1.6	1.6	1.6	1.6
area ratio into nozzle	100	100	100	100	100
area ratio out of nozzle	2500	2500	2500	2500	2500
nozzle exit area [m^2]	0.001963496	0.001963496	0.001963496	0.001963496	0.001963496
iterated parameters:					
stagnation pressure [Pa]	327280	567500	259980	324470	209230
nozzle exit mach no.	13.79	34.18	9.69	13.79	11
calculated parameters:					
gas density in heater [kg/m^3]	4.192457471	10.02448978	5.059331058	4.019219716	1.666727208
gas density out heater [kg/m^3]	0.681618907	1.62980348	0.822557112	0.653453534	0.270980156
mass flow rate [kg/s]	0.000254084	0.000548734	0.000241626	0.000247707	0.000125791
estimated discharge time [h]	16.39875	10.47865625	26.21129167	16.26023958	20.6029725
flow velocity in heater [m/s]	0.771648326	0.696963515	0.608080246	0.784705838	0.960936757
flow velocity out heater [m/s]	4.746204592	4.286838092	3.740140632	4.826517894	5.910467624
mach no. out of heater	0.005788866	0.005626703	0.005861963	0.005788819	0.005834668
area ratio into nozzle	99.97041052	99.9684266	99.97336761	99.97122409	99.97487044
nozzle exit velocity [m/s]	6290.324703	2915.12368	6608.388351	6452.329604	12704.36868
nozzle exit area [m^2]	0.001960071	0.001963311	0.001960641	0.001960071	0.001961564
nozzle exit pressure ratio	2.69151E-06	3.33089E-07	6.35753E-06	2.69151E-06	4.6438E-06
nozzle exit pressure [Pa]	0.880875874	0.189027822	1.652829745	0.873312744	0.971621884
nozzle exit temperature [C]	42.86136641	4.282947481	115.2121463	42.86136641	80.03061542

Appendix E
Pressure Transducer Selection

For proper flow control, some method of measuring the pressure downstream of the pressure regulator is necessary. That is, given desired input power and thrust levels, if the waste gas composition changes, the current pressure must be monitored in order to compute the necessary change. Rather than designing transducers specifically for resistojet application, catalogs of existing stock items were consulted. From one Omega handbook, several sensors with operating capabilities comparable to those required by the resistojet were found, and are shown in Table 9 [1989].

Table 9. Pressure Transducers [Omega, 1989]

Model #	Pressure range (psig)	Temperature range (°C)	Response time (ms)	Accuracy % of full scale	Corrosion Resistance?	Cost ($)
PX-236	0 - 100	-30 to 70	1.0	± 1.5	No	85
PX-180	0 - 100	-55 to 75	2.0	± 0.3	Yes	125
PX-120	0 - 100	-40 to 125	5.0	± 1.0	Yes	150
PX-300	0 - 150	-29 to 60	2.0	± 0.5	No	125

The transducer was selected for meeting the temperature and pressure ranges (i.e. -1 °C and 0-83 psia, respectively) at the point of installation just downstream of the regulator. Also, other factors considered were response time, accuracy, corrosion resistance, cost, and durability. Durability was not listed in the Table, because all transducers considered were specified with an operating life of 100 million pressure cycles [Omega, 1989]. Based on these specifications, model #PX-180 was chosen for its superior accuracy and corrosion resistant housing. However, one slight modification must be made in order to integrate the transducer into the resistojet gas pipe. That is, the pressure port is too long, 1.715 cm, for pipe-fitting (i.e. diameter = 1 cm). Thus, it must be shortened to 3 mm to maintain sufficient strength in its attachment to the pipe, and yet allow the flow to pass with minimal disturbance.

Reference

Omega, Pressure, Strain, and Force Measurement Handbook, 1989.

Appendix F
Heater Tube Length Calculation

Assumptions:
Heater is 100% Efficient
Constant Wall Temperature
Constant thermal conductivity
Fully developed laminar flow

eater properties:

neater tube inside diameter	Dti	0.01	meters
power into heater	Pin	125	Watts
temp. of propellants into heater	Tin	77	deg C
temp. of propellants out of heater	Tout	1400	"
average wall temp. of pipe	Twavg	1500	"
logarithmic mean temp. difference	LMTD	498	"

Analysis:
Apply an energy balance to the heater Pin = h*A*LMTD
Solve for the required length L = Pin / (h*Pi*Dt*LMTD)

Results: Propellants	**Air**	**H2O**	**Ar**	**N2**	**CO2**
thermal conductivity k (W/m-K)	0.0675	0.0981	0.0427	0.0648	0.068
heat transfer coefficient h (W/m2-K)	29.45	42.81	18.63	28.28	29.67
required length for exit @ 1400C (m)	**0.271**	**0.187**	**0.429**	**0.282**	**0.269**

Selection:
The final heater ler :h was set at **0.3** **meters**

Appendix G

Heater Coil Length and Wire Diameter Calculations

For uniform heating, the resistor coils must cover the entire surface of the heater tube. The heater tube will be threaded with a pitch of one wire diameter to ensure a perfect helical winding. This threading also prevents adjacent turns from touching and producing a short circuit. The threaded length is equal to the length of the resistor wire and is calculated to be:

$$L_w = \frac{\pi \cdot D_{to} \cdot L_t}{2 \cdot D_w} \qquad (1)$$

The coils must output up to 500 W by resistive heating, and Ohms law gives the relationship between power dissipated (P_{in}) and wire length:

$$P_{in} = R \cdot I^2 = \frac{4 \cdot \rho \cdot L_w}{\pi \cdot D_w} \cdot I^2 \qquad (2)$$

Combining Equations (1) and (2) we define an expression relating resistor wire diameter to resistivity of the wire material:

$$D_w = \sqrt{\frac{2 \cdot D_{to} \cdot L_t \cdot \rho \cdot I^2}{P_{in}}} \qquad (3)$$

The following spreadsheat shows the iterative method used to determine the lenght and diameter of the resistor wire

Diameter and Length Calculations for Resistor Wire

Assumptions:
Ignore possible inductance effects
Constant resistivity

Heater Properties:

heater tube outside diamete	Dt	0.014	meters
power into heater	Pin	500	Watts
heater tube length	Lt	0.3	meters

Analysis:
Choose a material therefore specifying the electrical conductivity
Molybdenum r (Ohms-meter) 2.64E-07

Calculate wire diameter	Dw = ((2*Dw*L*r*I^2) / Pin)^(1/3)
Calculate length of wire	Lw = (Pi*Do*L) / (2*Dw)

Results:

Choose input current I (A)	10	20	30	35	40
Wire diameter (Dw)	0.0008	0.0012	0.0016	0.0018	0.0019
Length of resistor wire (m)	8.65	5.45	4.16	3.75	3.43

Selection:

The final resistor wire is of Molybdenum	**Dw**	**0.002**	**meters**
	Lw	**3.4**	**meters**

Appendix H
Outer Sheath Heat Transfer Analysis

A critical aspect of the design of the resistojet is that of the outer sheath. This sheath must provide a protective housing for the inner components of the jet, as well as minimize radiative heat loss. In this design, heat transfer was the primary design characteristic. The first step in the analysis was setting the goal efficiency of the heater. For this design, a minimum acceptable efficiency of about 96 percent for the heater was used, yielding a maximum heat loss of 20 W at 500 W input power. Also, the outer temperature was designed for a maximum of 400°C, which would limit the amount of heat which was lost to space.

Certain assumptions were also made for the casing. Space was assumed to have a temperature of 0 K and an emissivity of 1.0. Radiation was considered negligible at the nozzle-end of the jet, and the view factor between the sheath and the outer surface was assumed to be unity. For the outer casing, the emissivity was designed for a value of 0.25. Using the Stefan-Boltzmann law [Bayazitoglu and Ozisik,1988], the heat flux was calculated:

$$q = \frac{\sigma \cdot [T_1^4 - T_2^4]}{[(1/F_{1-2}) + (1-\varepsilon_1)/\varepsilon_1 + (1-\varepsilon_2)/\varepsilon_2]}$$

which equaled 290.3 W/m^2, a rough approximation for the surface radiative flux. Dividing total heat loss by the heat flux, the outer surface area was determined to be 0.0689 m^2 with a diameter of 7.3 cm.

Using the previously stated target value of 0.2 for emissivity, Iconel X was determined to be the best material [Howell, Bannerot, and Vliet, 1982]. Iconel X has an emissivity of 0.2, which falls within the assumed value. In addition, Iconel X is a stainless steel, which means that the outer surface will have a favorable combination of toughness and tensile strength. The surface will also remain non-reactive with components of the plume gases, which may be deposited on the surface [Howell, Bannerot, and Vliet, 1982]. To ensure the structural integrity of the casing, the inner diameter of the casing was set at 7.3 cm and the outer diameter set at 8.3 cm. This increase in diameter resulted in a sheath thickness of 5 mm, making the structure more reliable. The increased diameter also did not appreciably change the overall heat transfer characteristics.

Appendix I
Radiation Shield Analysis

The primary mode of heat loss in the resistojet is through radiation. Steps must be taken to reduce this radiative heat loss and improve the jet's overall efficiency. The solution to this problem is radiation shields placed concentrically around the heater assembly. The key to designing the radiation shields is to reduce the temperature as much as possible over the 2.95 cm distance between the heater and casing without allowing conduction of the heat.

To accomplish this task, the shield design will use foil radiation shields. These sheets will be thin enough to allow multiple shield placement without risking heat conduction. Also, the low thickness and high conductivity of the foils will make the temperature gradient very small through the sheet, simplifying the heat transfer analysis [Bayazitoglu and Ozisik, 1988].

The first part of the analysis involves material selection. Platinum shields will be used to withstand the 1600°C temperature of the heater surface, and stainless steel 410 will be used for the cooler shields placed further from the heater. Since platinum is about three times heavier than SS 410, the platinum shields will be used only to reduce the temperature below the melting point of the stainless steel shields [Metals Handbook, 1985]. Foil thickness of the shields will be 0.1 mm for platinum and 0.15 mm for SS 410.

Several assumptions were made for this analysis. The shield system was approximated as a series of parallel plates, with view factors $F_{n,\,n+1} = 1.0$. Surface areas were taken at a mean distance between two shields, and heat power was assumed as 10 percent of the power setting. Foil spacing was assumed to be 1.5 mm, or 10 times the highest foil thickness. Using a modified version of the radiation equation, where e = emissivity and n = number of shields in series,

$$Q_n = \frac{A_{to} \cdot \sigma \cdot [T_1^4 - T_2^4]}{[(n+1) \cdot (2/\varepsilon - 1]}$$

for heat transfer between each shield [Bayazitoglu and Ozisik, 1988]. With this heat transfer analysis, the shield temperature drops to about 1380°C after two platinum shields. Carrying this analysis out further using the values for SS 410, it was found that

13 stainless steel shields would be needed to reduce the outer sheath temperature to 400° C.

Using the number of shields with their thicknesses and spacing, the available 2.95 cm was quite adequate to prevent shield contact. Spacing for the shields will involve winding 1.5 mm diameter wire around the heater and shields at various locations. The remaining space of 6.35 mm was divided into a shield/casing clearance of 2.175 mm, and a heater/shield clearance of 4.175 mm. Extra clearance was allowed between the inner shield and heater to provide more space for the heater coil winding.

Appendix J
Seals

An important issue with the resistojet is environmental contamination. The system must be effectively sealed against leakage. Both welding processes, and polymer and metallic seals were considered to join the components and provide leak protection.

Seals are catagorized as static or dynamic depending on whether there is relative motion between the seal and the components it is sealing [Goetzel, 1965]. Common resistojet materials were selected for each component so that, when thermal expansion occurs, the relative motion between components would be minimized. However, due to nperature gradients, dynamic seals will be required. For use in a propuls[illegible]n system, [illegible]tzel [1965] recommends stainless steel and aluminum alloys, teflon, an[illegible] [illegible]on. H[illegible]vever, these materials can not withstand the 1400 °C temperature seen at [illegible]heater exit. Therefore, seals will be used for all component junctions except that at the heater exit, where welding will be considered.

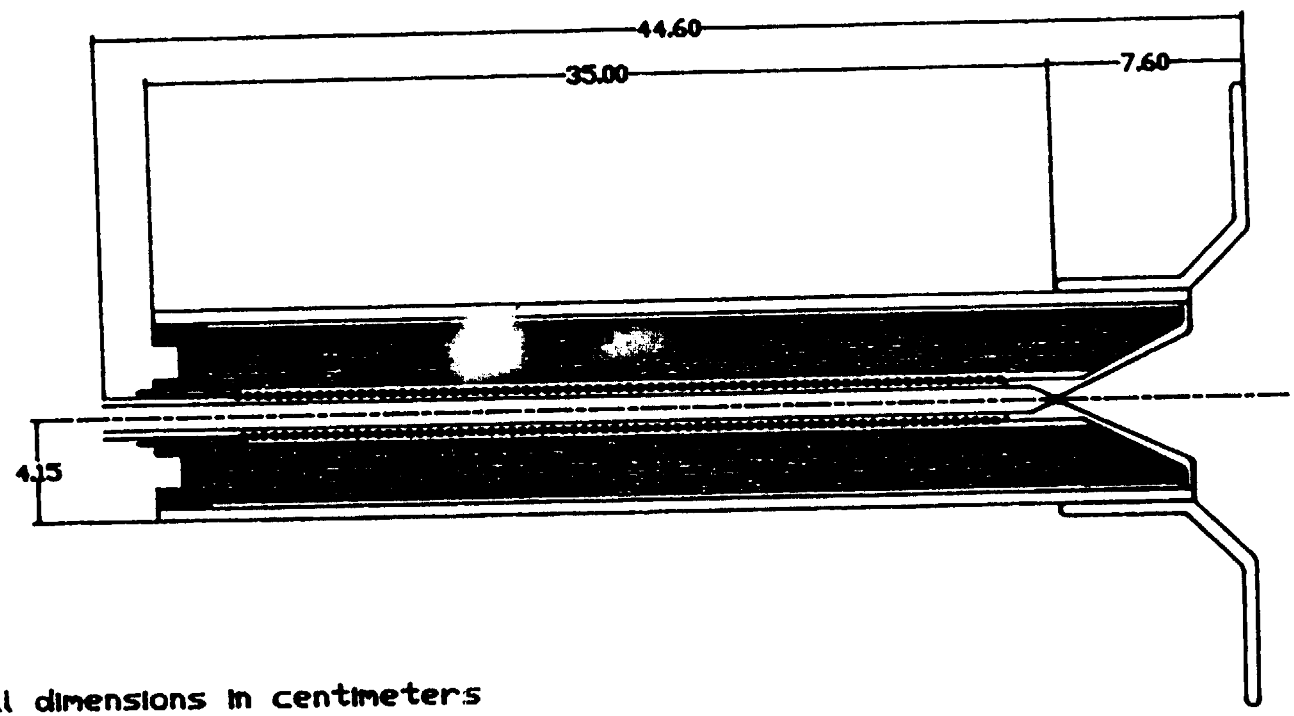
Among the three recommended seals, stainless steel was chosen for its operating range (-252 to 648 °C), its excellent corrosion resistance to each of the waste gases, and its radiation stability in a vacuum. The selection over the teflon and nylon elastomers was based on the fact that metallic seals are developed for their capability of not being affected by radiation [Goetzel, 1965].

Among the welding processes considered, diffusion welding was selected based on the fact that similar metals will be welded, and that better bonding is obtained when the temperature is high enough to ensure diffusion, typically above half the melting temperature [Schey, 1987]. The melting temperature of Platinum, the heater tube and nozzle material subject to 1400 °C, is 1770 °C. Grain stabilization, as explained in the heater material selection, was introduced to impede diffusion. Thus, for diffusion bonding to work, the nozzle and heater must be welded before grain stabilization. Since a common material was chosen, there will be no relative motion due to thermal expansion, and thus no resulting shear stresses on the weld. The only force that the weld must support, assuming no impact of micrometeorites, is that of the thrust. Thus, diffusion bonding before the grain stabilization is chosen as the heater/nozzle seal.

Appendix K
Detailed Drawings for the Resistojet

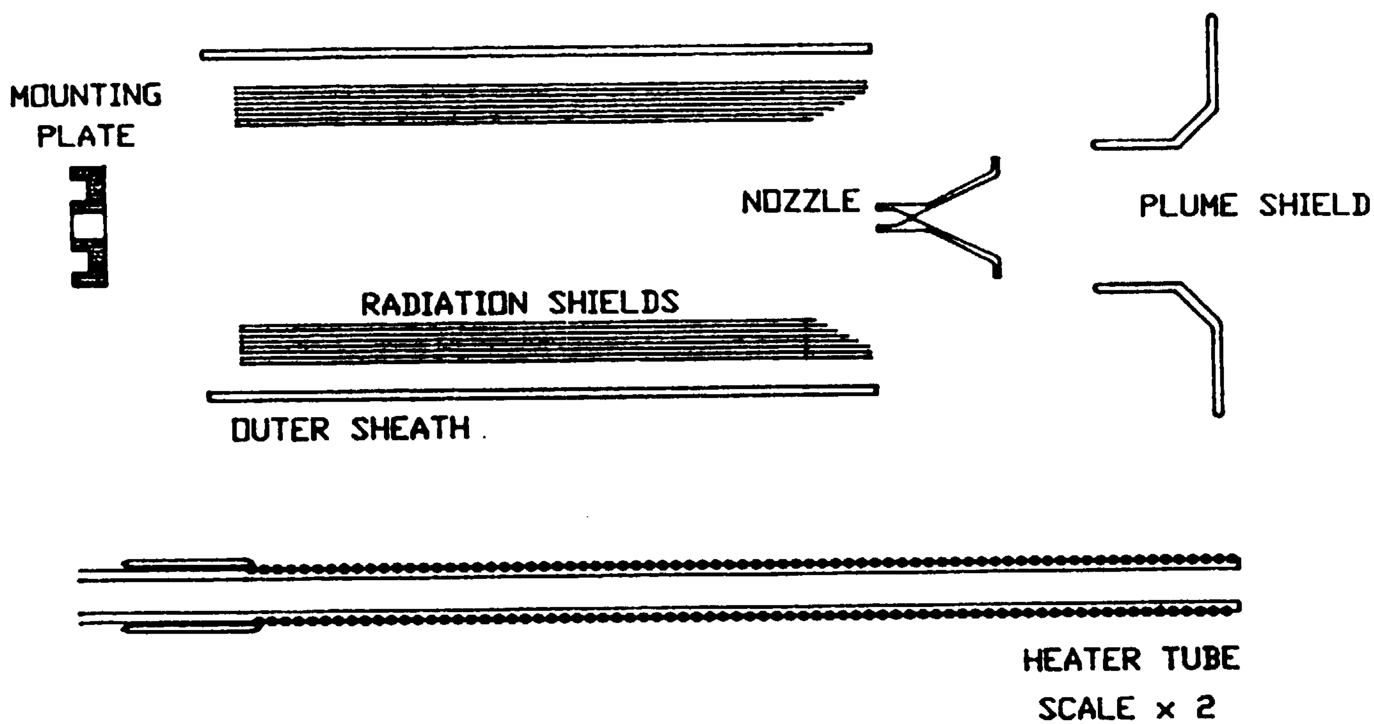
List of Drawings

ASSEMBLED RESISTOJET

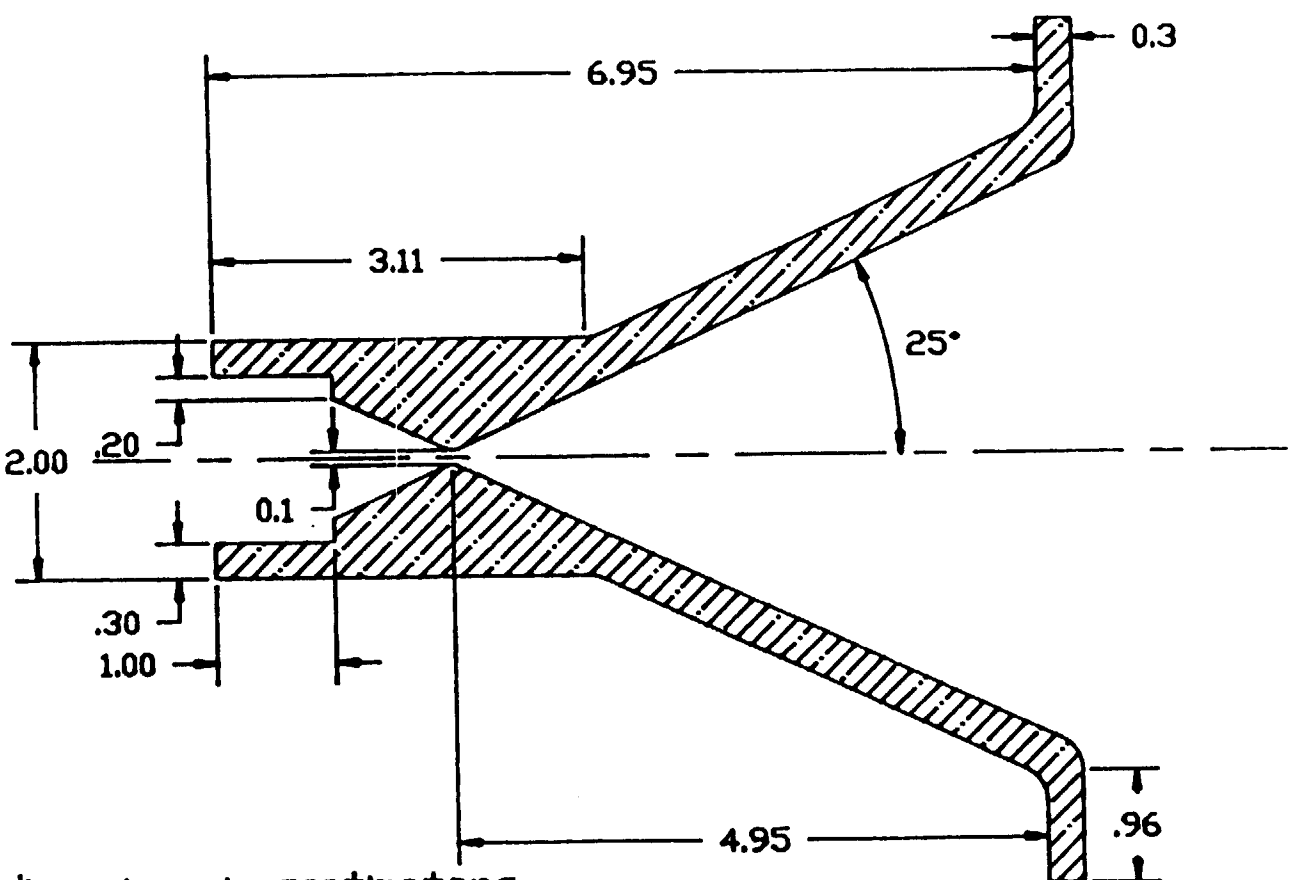


Note: all dimensions in centimeters

RESISTOJET COMPONENTS

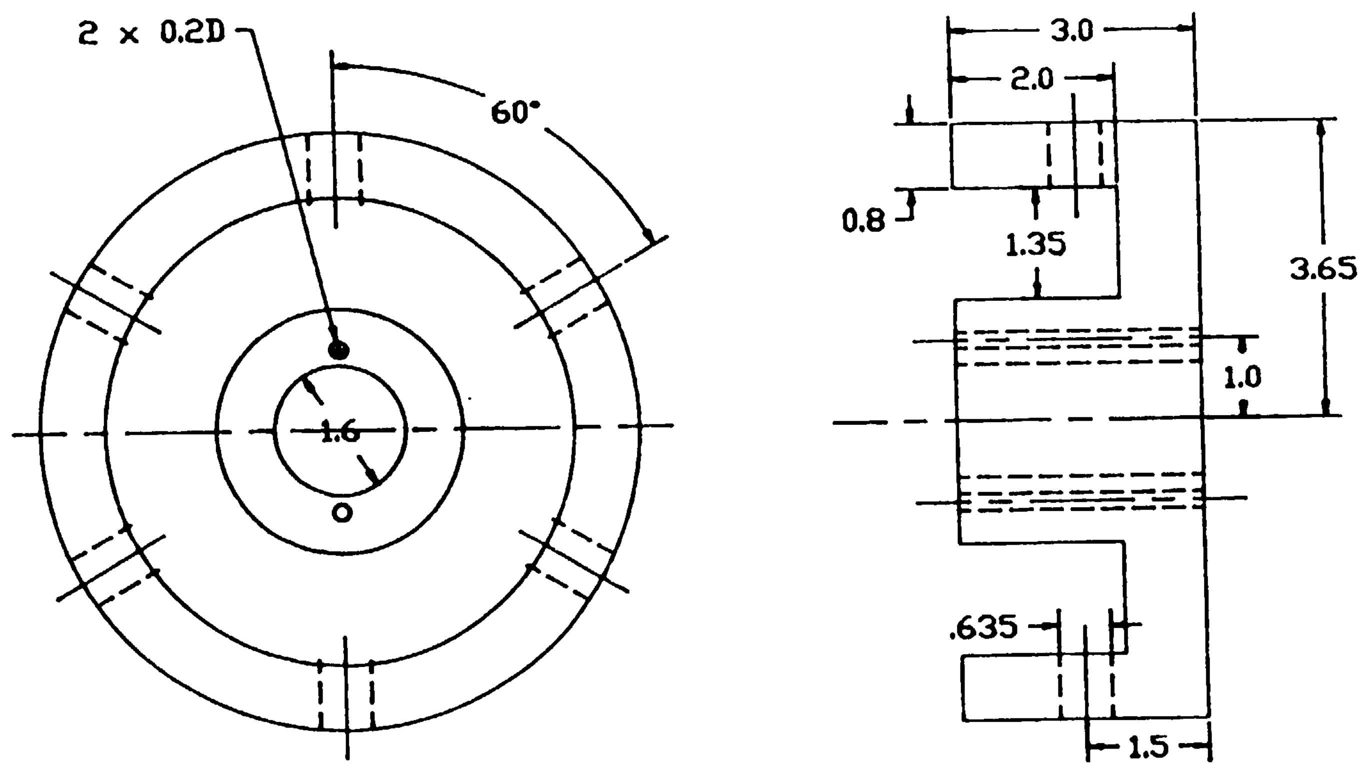


NOZZLE



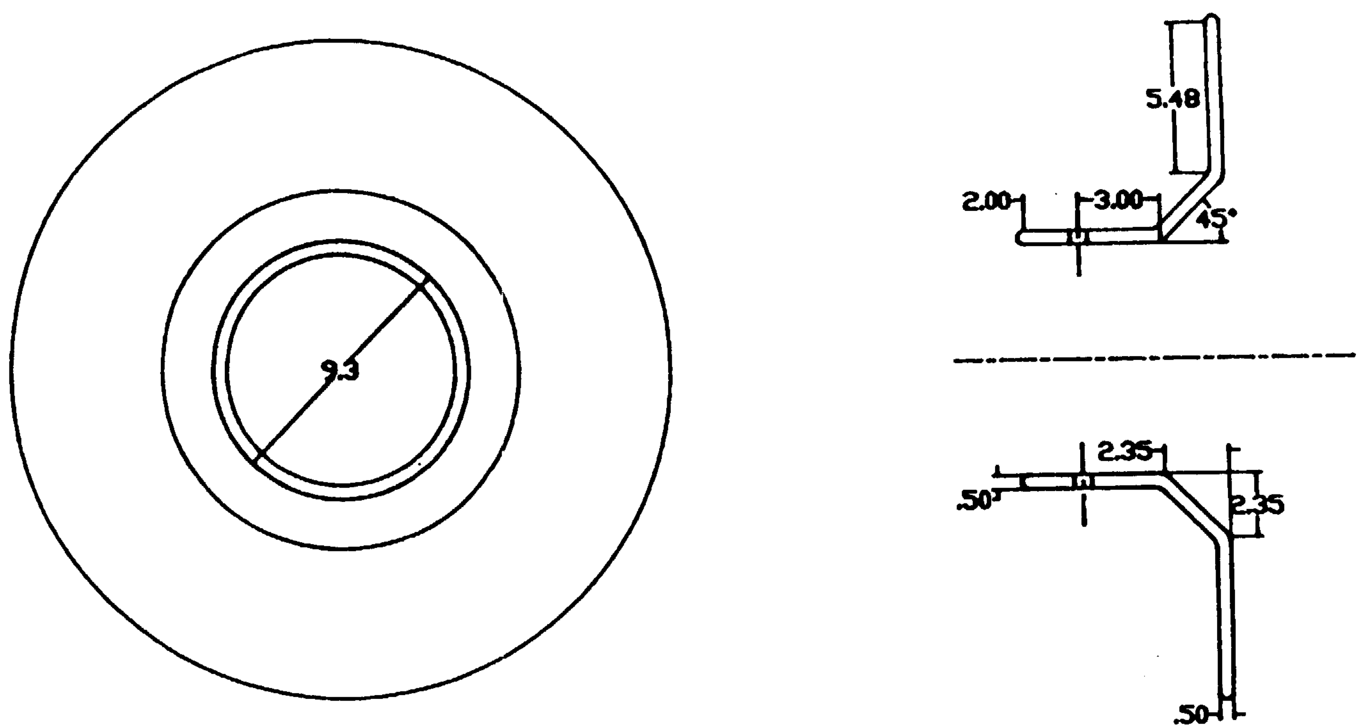
Note: all dimensions in centimeters

MOUNTING PLATE

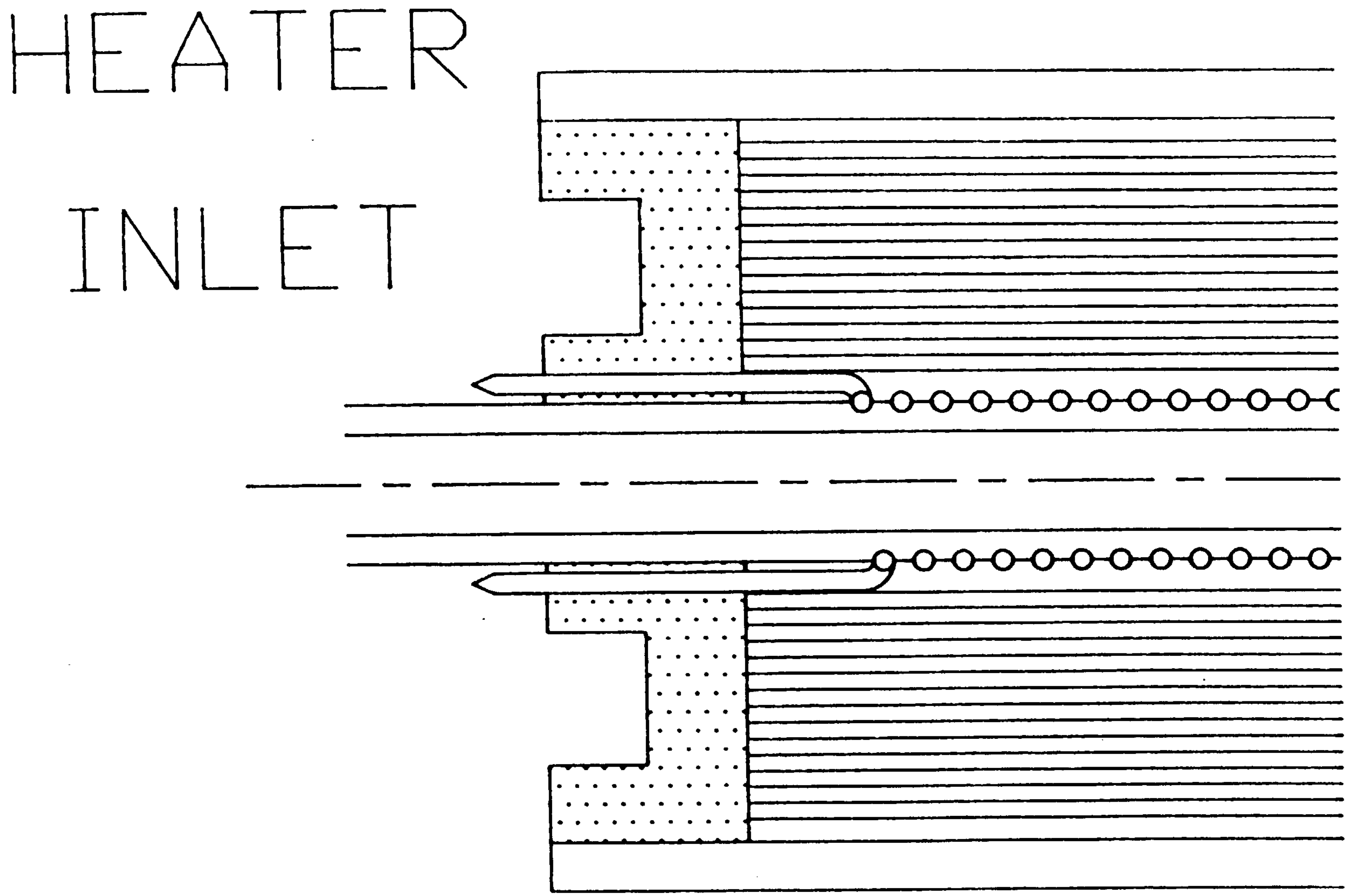


Note: all dimensions in centimeters

PLUME SHIELD



Note: all dimensions in centimeters


HEATER
INLET